

Development and Demonstration of Hydrogen and Compressed Natural Gas (H/CNG) Blend Transit Buses

October 15, 2002 — September 30, 2004

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Technical Report
NREL/TP-540-38707
November 2005

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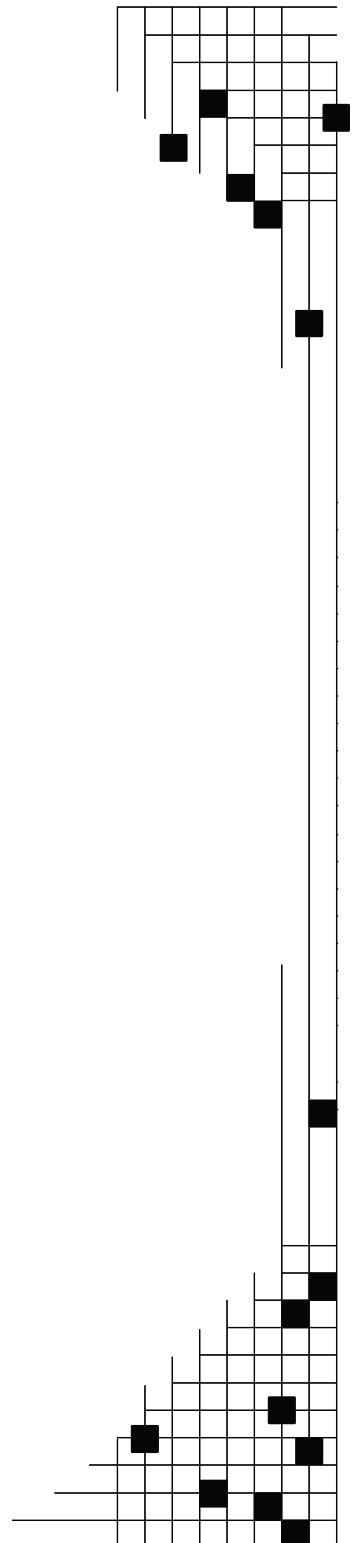
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Acronyms and Abbreviations

bmep	brake mean effective pressure
BSFC	brake specific fuel consumption
CH ₄	methane
CNG	compressed natural gas
CO	carbon monoxide
CSHVR	City-Suburban Heavy Vehicle Route
CWI	Cummins Westport Inc.
DGE	diesel gallon equivalent
FTI	Fueling Technologies Inc.
H	hydrogen
HCI	Hydrogen Components Inc.
hp	horsepower
NMHC	non-methane hydrocarbons
NO _x	oxides of nitrogen
NREL	National Renewable Energy Laboratory
OCTA	Orange County Transit Authority
PM	particulate matter
psi	pounds per square inch
SAE	Society of Automotive Engineers
SCAQMD	South Coast Air Quality Management District
SCF	Standard cubic feet
SI	spark ignited
SS	steady state
THC	total hydrocarbons
WVU	West Virginia University

Executive Summary

Natural gas is a domestically available energy source with a variety of consumers including residential, commercial, industrial, electrical generation, and automotive. While liquid petroleum fuels are the current standard for automotive applications, some believe that hydrogen is the future automotive fuel of choice. A transition to hydrogen-fueled automobiles will undoubtedly take a significant amount of time and a number of intermediate steps. One approach being suggested as an early step is the concept of blending hydrogen with compressed natural gas (H/CNG) for use in state-of-the-art internal combustion engine vehicles. Current natural gas engines and vehicles can be modified to operate on H/CNG with available technology. A small-scale study of this concept was completed.

Literature and laboratory analyses were undertaken to identify modification requirements of a Cummins Westport, Inc. (CWI) B Gas Plus natural gas engine for H/CNG use in a transit bus application. Previous studies indicate that H/CNG mixtures with 20 to 30 vol% hydrogen are optimal for performance and emissions in existing engine designs. Necessary hardware modifications included changing the fuel flow sensor on the engine and increasing on-board fuel storage. Four transit buses, two fueled with CNG and two fueled with H/CNG, were operated and monitored for 24,000 in-service miles with the SunLine transit fleet in Thousand Palms, CA. Additionally, chassis dynamometer emission testing of the four buses was completed.

The results of an initial engine dynamometer laboratory assessment of the effect of hydrogen blend level on emissions and fuel economy led to the selection of 20 vol% hydrogen for use in this study. In additional laboratory testing, the H/CNG engine showed regulated pollutant reductions for oxides of nitrogen (NO_x), non-methane hydrocarbons (NMHC), and carbon monoxide (CO) of 50%, 58%, and 9% respectively with no fuel consumption penalty relative to CNG.

Over a nine month period, the CNG and H/CNG buses operated 88% and 84% of the time respectively during regularly scheduled transit service, with all buses exceeding the 24,000 mile target. Fuel economy during the in-use assessment shows the H/CNG vehicles actually used more fuel on an energy equivalent basis. In contrast to engine testing results, on average H/CNG fuel consumption was 12% higher during the in-use assessment than for CNG. In-use exhaust emission characterization supports the laboratory results for NO_x; H/CNG vehicles averaged over 55% reduction on two separate test schedules. Measurements for all other regulated pollutants were very low for both fuels because of the presence of oxidation catalysts on all the vehicles. A post service assessment of the vehicles showed no differences in engine wear between the two fuels.

This project demonstrated that with minor engine and vehicle modifications the 20/80 H/CNG blend can be used in revenue service fleets with similar operational performance as CNG. Additional optimization of the H/CNG engine calibration is necessary to attain equivalent fuel economy, or alternatively increased fuel economy at equivalent NO_x emissions.

Background

Since their introduction in the early 1990s, natural gas vehicles have demonstrated significantly lower exhaust emissions compared to their diesel-fueled counterparts, particularly in the regulated constituents of particulate matter (PM) and oxides of nitrogen (NO_x). Natural gas vehicles can reduce PM by over 90% and oxides of nitrogen by 50% or more in some cases.

A possible approach for meeting future emission regulations with current natural gas engine designs is to blend hydrogen with compressed natural gas (CNG). This allows leaner air/fuel ratio and retarded spark timing. Combined, the lean air/fuel ratio and retarded timing can reduce NO_x considerably without the use of exhaust after-treatment equipment. In addition, blending hydrogen with compressed natural gas (also referred to as H/CNG) has the potential to be a cost-effective “bridge” to a hydrogen transportation future. H/CNG could facilitate the early introduction of hydrogen as a transportation fuel using technology that is very near commercialization.

To demonstrate the viability of H/CNG as an automotive fuel, this H/CNG transit bus development and demonstration program was initiated. SunLine Services Group was selected as a fleet partner, in part, because of their ten years of gaseous fuel experience in transit use including four years with gaseous hydrogen. SunLine operates the world’s first transit hydrogen generation, compression, storage, and public dispensing station, which was opened in April 2000.

Project Partners

This project was conducted with funding support from the National Renewable Energy Laboratory (NREL) and the South Coast Air Quality Management District (SCAQMD). NREL wishes to acknowledge funding from the U.S. Department of Energy, Office of FreedomCAR and Vehicle Technologies, Fuels Technologies Program. The Project Team consists of:

- SunLine Services Group, which conducted revenue service field testing (both in-service operation and engine evaluation) with support from SunLine Transit Agency, both located in Thousand Palms, CA
- Cummins Westport, Inc. (CWI), which conducted the extensive H/CNG engine design, development and optimization effort, and
- Hydrogen Components, Inc. (HCI); F. Lynch, served as advisor to the project.
- The National Renewable Energy Laboratory was responsible for overall project coordination and direction.

Project Goals and Objectives

The project goal was to define engine design or hardware modification requirements and perform in-use assessment of H/CNG fueled vehicles as a potential transition technology and path to using hydrogen in the commercial transportation sector.

Project objectives established to support these goals included:

- Determine the optimum H/CNG blend for near-term, practical use.
- Develop and optimize an engine calibration for H/CNG and quantify performance with engine dynamometer testing.
- Verify vehicle performance and component compatibility of CNG engines with H/CNG blend for 24,000 mile in-use assessment.
- Characterize in-use emissions results with chassis dynamometer testing.

Prototype Engine and Vehicle Development

Technical Assessment

The prototype engine/vehicle system development began with a technical assessment that included an extensive literature review of research previously conducted or underway regarding blended gaseous fuels. This literature review was conducted to uncover existing research on H/CNG mixtures used for lean-burn spark-ignited engines. Previous studies indicate that H/CNG mixtures with hydrogen content in the range of 20 to 30 volume percent (vol%) are optimum in terms of performance and emissions benefits, while still providing operation within the limits of the existing engine hardware.

H/CNG Combustion

Early research on hydrogen enrichment was focused on fuels such as gasoline and isooctane [1,2]. These experiments established the effectiveness of hydrogen in extending the lean operating limit as well as reducing NO_x emissions and increasing thermal efficiency. Later studies of hydrogen enrichment have focused on natural gas utilizing lean-burn, spark-ignited (SI) engines [3 through 6]. H/CNG mixtures with 0, 5, 15, and 30 vol% hydrogen were tested using a GM 5.7L, V8 engine. The H/CNG blends between 15 vol% and 30 vol% hydrogen enabled very lean operation and NO_x emission reductions with some penalty in total hydrocarbon (THC) emissions.

Brake-mean effective pressure (BMEP) is the work performed by the engine per cycle divided by the cylinder volume displaced per cycle. BMEP is an accepted metric to assess an engine's ability to do work and is independent of engine size. Figure 1 shows the theoretical and actual BMEP difference of a 30 vol% H/CNG fuel mixture relative to CNG. Despite its low energy density, hydrogen can improve engine performance at very lean engine operation because it releases more energy per unit oxygen consumed. Moreover, the increased flame speed and lean combustion ability of hydrogen increase the combustion efficiency significantly.

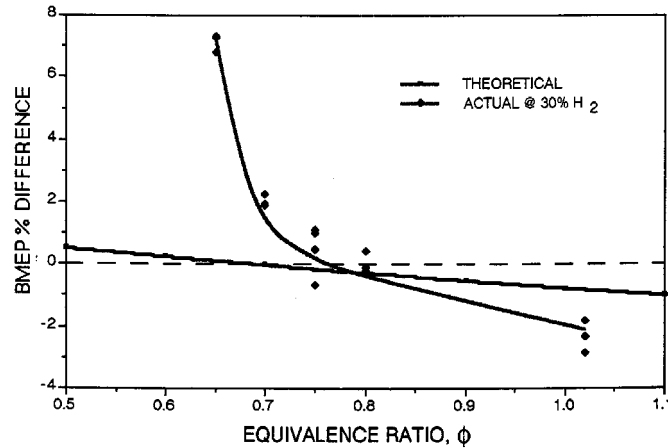


Figure 1. Comparison between theoretical and actual BMEP change with 30 vol% hydrogen in methane [5].

Figure 2 shows the effect of air/fuel ratio relative to NO_x production. The largest amount of NO_x is produced where the air/fuel ratio is slightly lean of stoichiometry and is denoted 100% NO_x. Further leaning of the air/fuel mix reduces NO_x. Current natural gas engine products including the CWI B Gas Plus are operated with a very lean air/fuel ratio as noted by the shading. Blending 15 vol% to 30 vol% hydrogen into CNG fuel extends the lean combustion limit beyond current product capability, furthest right in the figure. To leverage the NO_x reduction of the extended lean limit, engine development would also include retarded spark timing investigations.

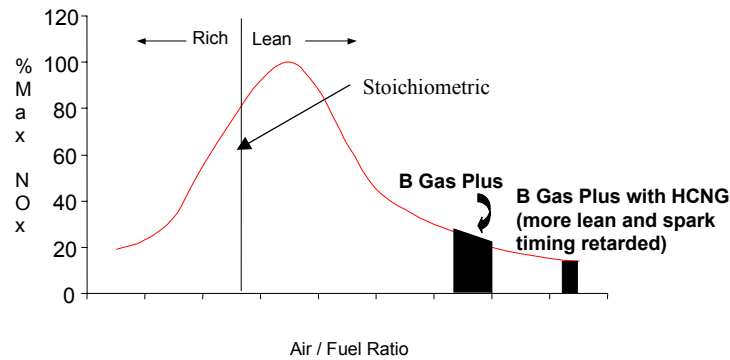


Figure 2. Effect of air/fuel ratio on percentage maximum NO_x emissions.

Fuel System Components

Due to the small proportion of hydrogen in the mixture (H/CNG blends up to 30 percent by volume or 5 percent by mass hydrogen were considered) the physical properties of the fuel mixture are close to the baseline natural gas fuel and do not impact components such as piping, valves, and storage tanks. The potential for hydrogen embrittlement is expected

to be quite low because component materials found in the fuel system are carbon steels, stainless steels, aluminum alloys, copper, and copper alloys, which are acceptable for gaseous hydrogen service at ambient temperatures.

The fuel flow rate sensor is based on a hot-wire system that uses thermal conductivity of the gaseous fuel to measure the fuel flow rate. At similar conditions, hydrogen has over six times higher thermal conductivity compared to natural gas. Thus, the H/CNG mixture will have higher thermal conductivity and will saturate the output of the fuel flow rate sensor towards the maximum flow rate conditions. The fuel metering requirements are in the range of 0-40 kg/hr depending on the speed and load. A production fuel flow rate sensor from a larger displacement (8.9 L) CWI natural gas engine was determined to have sufficient capacity for the required flow rates and was installed.

Tank Core Temperature

The literature review of other H/CNG demonstrations raised some concerns regarding rapid fueling of the H/CNG bus with the blended fuel and its potential to raise the tank core temperature beyond design limits. An evaluation was conducted to determine if the cylinder tank temperature would exceed the manufacturer's recommended tank temperature (85°C) during refueling. This was of specific concern to SunLine due to the unusually high ambient temperatures experienced in the region's hot desert climate.

In order to ensure that the fuel tank design temperature was not exceeded with the new fuel blend, the tank core and exterior tank temperatures were measured and a tank pressure transducer was also installed for this evaluation. Data were collected during fast fill of the vehicle fuel tank. The results indicated that the outer tank core temperature reached 40°C and the inner tank temperature reached 64°C; this was demonstrated with an ambient temperature around 30°C. Because local ambient temperatures can reach 48°C, a model was developed to simulate the higher ambient temperature. Using a 48°C ambient temperature, the model predicted average inner core gas temperature was 70°C. Since the maximum design limit is 85°C, it was determined that fueling with H/CNG did not compromise tank operation.

A detailed report on the tank temperature studies can be found in Appendix A.

H/CNG Blend Level Determination

Laboratory Analysis

To assess the differential effects from varying levels of hydrogen in the H/CNG fuel blend, engine test data were needed. Data needs included emission rates of NO_x and THC as well as fuel consumption. To get a fair representation of the engine map, four distinct steady-state (SS) engine-operating points (engine speed and load) were chosen (Table 1). At each SS point data were collected and used to optimize the spark-timing and air/fuel ratio for the different H/CNG fuel blends from 20 vol% to 32 vol% hydrogen. An optimized SS point was found using a combination of spark timing retardation and leaning the air/fuel mixture while keeping the torque, fuel consumption, and THC emissions near the natural gas baseline.

Table 1: Steady-state operating points used for H/CNG blend investigation

Test Point	Engine Speed [RPM]	Torque [N-m]	Torque [Ft-lb]
1	1600	700	516
2	2800	587	433
3	1769	301	222
4	2534	172	127

It should be noted that the engine has closed loop air/fuel ratio control and is equipped with a waste-gated turbocharger and an electronically controlled intake throttle. These features allowed the engine to maintain torque under H/CNG operation at higher air/fuel ratios and retarded spark timings by increasing the intake airflow while keeping the fuel energy flow rate the same as for natural gas operation.

The laboratory data analysis is summarized in Table 2. The measured parameters (NO_x , total hydrocarbon (THC), and brake specific fuel consumption (BSFC)) are an average of the four SS operating points using optimized timing and air/fuel ratio. The 25 vol% H/CNG yielded the highest average NO_x reduction but also increased THC. The 23 vol% H/CNG reduced NO_x with little change in THC and BSFC. However, looking at the NO_x reduction relative to the amount of hydrogen used, also noted as “leverage” in the table, the 20 vol% H/CNG looked favorable.

Table 2: H/CNG Blend Test Results Summary.

H ₂ Volume Fraction (%)	H ₂ Energy Fraction (%)	% Change Relative to CNG*			Leverage (% NO_x reduction/ H ₂ Energy)
		NO_x	THC	BSFC	
20	6.9	-59.7	+7.8	+2.3	8.7
23	7.7	-62.7	+3.0	+1.5	8.2
25	9.0	-74.2	+12.8	+1.0	8.3
32	12.2	-67.7	+2.8	+1.5	5.5

* Average of the four SS points (from Table 1) with optimized timing and air/fuel ratio

Practical Analysis

Taking into consideration the project objectives, engine development constraints and economics, a weighted blend analysis comparison was assembled. Each blend was rated in five categories: NO_x reduction, engine performance, maintenance & repair, equipment modification, and fuel cost. NO_x reduction, equipment modification, and fuel cost were weighted twice as much as engine performance and maintenance & repair. Using these criteria, the 20 vol% and 23 vol% H/CNG blends were even as shown in Table 3.

Table 3: Weighted H/CNG blend analysis.

	NO _x Reduction	Engine Performance	Maintenance and Repair	Equipment Modification	Fuel Cost	Total
Weighting Factor	10	5	5	10	10	
20 vol%	2	4	4	5	5	160
23 vol%	3	4	4	5	4	160
25 vol%	4	3	3	3	3	130
32 vol%	3	2	1	1	2	93
A scale factor of 1 to 5 has been used to rate each point, with 1=lowest/least						

Ultimately the analysis methods did not clearly favor either the 20 vol% or 23 vol% hydrogen blend. The consensus between the project partners was to use a lower level of hydrogen. Slightly less hydrogen benefited several project criteria including the economics.

Engine Optimization

Engine Development Constraints

Key development program requirements for the H/CNG engine included:

- Maintain or improve horsepower and torque relative to the natural gas engine with minimal hardware changes.
- Pre-catalyst total hydrocarbon emissions should not increase relative to the natural gas engine.
- Maximize the NO_x reduction benefit relative to the baseline natural gas with minimal hardware changes.
- Maintain or improve thermal efficiency of the engine relative to the natural gas engine with minimal hardware changes.

The optimization strategy used for the H/CNG calibration was to lean the air/fuel mixture and retard the spark timing (relative to the CNG) in order to optimize NO_x reduction while maintaining torque, fuel efficiency, and other emissions similar to the CNG baseline. After calibration, the engine was tested over the AVL8 steady state test cycle to predict cycle averaged fuel efficiency and emissions. The engine performance (horsepower and torque) was verified by testing the engine at full torque over the engine speed range. Figure 3 shows the engine in the test cell during the optimization phase of the project.



Figure 3: Engine test cell with B Gas Plus engine installed and connected to the Dynamometer.

H/CNG reduced engine out NO_x and non-methane hydrocarbons (NMHC) emissions by 50% and 58%, respectively, as shown in Table 4. Engine out methane and THC emissions were reduced by 16% and 23%, respectively. There was no significant change in fuel efficiency. A short drivability study using a chassis dynamometer test cycle developed based on typical school bus operations verified the ability of the engine to maintain the transient speed and torque capability under H/CNG fueling.

Table 4: Engine out (pre-catalyst) AVL Cycle Composite Emissions

Emissions (g/bhp-hr)	CNG	H/CNG at 20 vol%	% Difference
NO_x	2.0	1.0	-50%
NMHC	0.24	0.10	-58%
NO_x +NMHC	2.24	1.10	-51%
CH_4	3.0	2.5	-16%
THC	3.4	2.6	-23%
CO	2.3	2.1	-9%

Engine Torque Curve and Maximum Power Comparison

Engine performance was verified by comparing the torque curves for each fuel. The torque curve demonstrates the capability of the engine to maintain full load under H/CNG fueling. Results are shown in Figure 4 comparing full torque achieved under natural gas and H/CNG fueling. As seen from the results, the H/CNG torque is either equal to or slightly higher than the torque generated with natural gas. The engine achieves a peak torque of 697 Nm at 1600 rpm and a rated torque of 596 Nm at 2800 rpm. Corresponding results for the engine power at full torque are also shown in Figure 4. The engine achieves a rated power of 237 HP at 2800 rpm under H/CNG fueling.

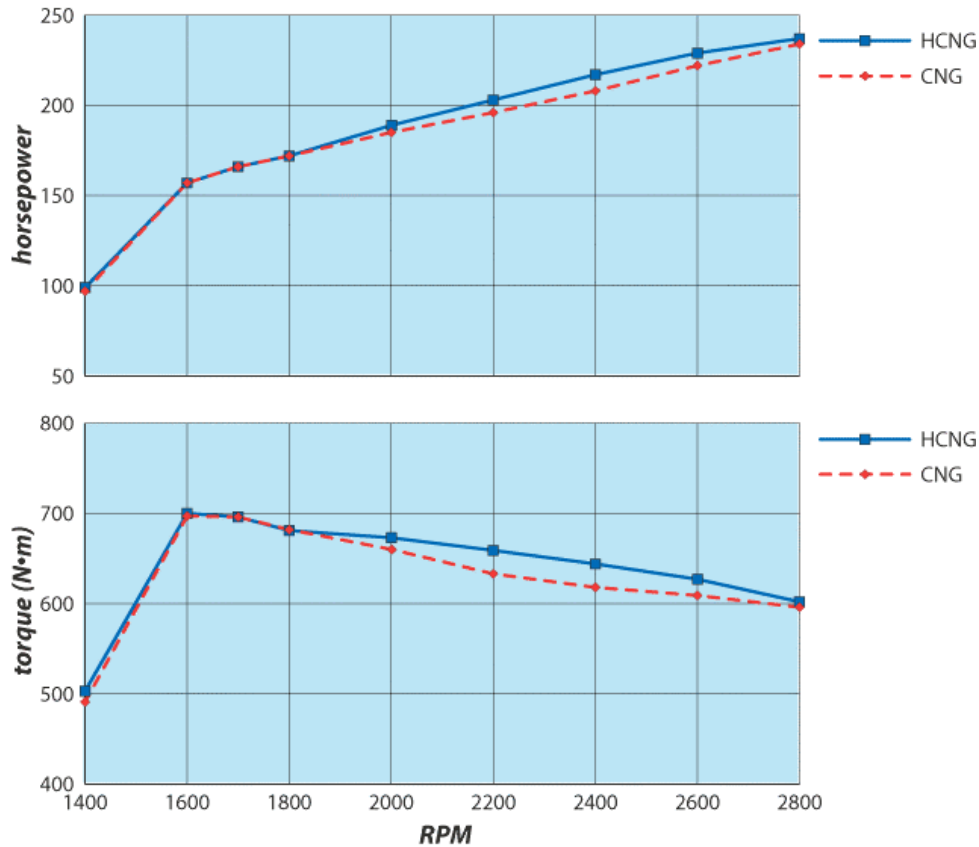


Figure 4. Comparison between CNG and H/CNG full torque and power curves.

In-Use Results from Revenue Service Operation

Vehicle Description

Four natural gas fueled Thomas Transit Liner buses were selected from the SunLine Transit Agency fleet for this development and demonstration program. The buses were previously equipped with Cummins B Gas engines. Three of the buses received CWI B Gas Plus engine upgrades. The fourth bus was re-powered with the original H/CNG development engine used in the engine optimization effort described in the previous section. The B Gas Plus engine design was selected to ensure that the developmental H/CNG calibration was assessed with the most recent natural gas engine design available from CWI. Two of the test vehicles were fueled with a 20/80 H/CNG blend, and the other two were fueled with CNG for the duration of the study.

Hardware changes necessary for H/CNG operation were relatively minor. The only change to the CWI B Gas Plus engine hardware was the fuel flow sensor. The fuel flow sensor measures thermal conductivity of the gaseous fuel for the fuel flow measurement the engine computer needs to determine the proper air/fuel ratio. It was replaced with another CWI production fuel flow sensor that has higher thermal conductivity capacities. This was necessary because of increased thermal conductivity of the H/CNG compared with CNG, as noted previously.

One vehicle modification was performed. The number of on-board fuel tanks was increased from five to eight for all four test buses. This provided added range and allowed for longer service routes. Table 5 shows a full list of engine and vehicle specifications.

Table 5: Engine and Vehicle Specifications

	H/CNG		CNG	
Chassis	1995 Thomas Transit Liner		1995 Thomas Transit Liner	
Engine Manufacturer & Model	1997 Cummins B gas 5.9L upgraded to 2003 Gas Plus specifications with modified engine calibration for HCNG fuel		1997 Cummins B gas 5.9L upgraded to 2003 Gas Plus specifications	
Engine Ratings	237 hp @ 2,800 rpm, 500 lb-ft @ 1,800 rpm		230 hp @ 2,800 rpm, 500 lb-ft @ 1,800 rpm	
Aftertreatment Equipment	Fleetguard Nelson Oxidation Catalyst		Fleetguard Nelson Oxidation Catalyst	
Transmission Manufacturer & Model	4-speed Automatic Allison MT643		4-speed Automatic Allison MT643	
GVWR/Curb Weight	36,200 lb / 24,750 lb		36,200 lb / 24,750 lb	
Bus Number	801	803	802	804
Starting Odometer Reading	115,809 mi	85,207 mi	104,747 mi	88,680 mi
On-Board Fuel Tanks	8	8	8	8
On-Board Fuel Storage	9,515 scf @ 70°F	9,515 scf @ 70°F	9,515 scf @ 70°F	9,515 scf @ 70°F

Blending and Dispensing Equipment

The H/CNG buses were fueled on-site with a dispenser supplied by Fueling Technologies Incorporated (FTI). The FTI dispenser mixed high-pressure hydrogen and natural gas for dispensing at a programmed 3000 psig. The dispenser was configured to provide an accurate blend of hydrogen and CNG on one hose and pure hydrogen on a second hose. Both fuels are measured using Coriolis type mass flow meters; the dispenser monitors the mass of each and injects hydrogen into the CNG flow as required to meet an accuracy of $\pm 2.0\%$. A dispenser control system monitors mass flow of hydrogen and CNG. Blend control valves on hydrogen and CNG lines are operated by the control system assuring accurate blending of fuels. It also controls temperature compensated filling pressure into the vehicles. Hydrogen and natural gas are blended to a programmable ratio in terms of volume, mass, or energy equivalent basis.

A unique nozzle is used for the H/CNG dispenser to prevent unintended fuel mixing with other vehicles operating on hydrogen or CNG. An LCD display informs the operator of the amount of fuel dispensed and a pressure gauge is also used verify the pressure

delivered. A gas detector/alarm system disables the dispenser under certain potentially hazardous conditions. The dispenser was configured to provide 20/80 by volume H₂/NG blend ratio. The accuracy of the H/CNG blend was verified from gas composition analysis of the samples taken from the gas supplied by the dispenser. The hydrogen content was found to be within 20 ± 1%. Appendix B shows the detailed fuel properties including percent hydrogen content for the H/CNG fuel.

In-Service Results

During the in-service assessment, October 2003 to June 2004, day-to-day operational data were collected for all four buses. The objective was to accumulate at least 24,000 revenue service miles on each vehicle to assess the feasibility of H/CNG operation in fleet service. During this period, SunLine used the standard maintenance schedule it applies to its entire CNG transit fleet. The following data are presented below:

- Mileage accumulation
- Fuel economy
- Days in service

Mileage Accumulation

After 9 months of data collection, all the test vehicles surpassed 24,000 in-service miles. The two CNG buses accumulated a total of 71,951 miles: 39,088 for bus 802 and 32,863 for bus 804. The H/CNG buses accumulated a total of 53,681 miles: 28,723 for bus 801 and 24,958 for bus 803. Figure 5 shows the mileage accumulation for all buses.

The difference in mileage accumulation between the CNG and H/CNG buses may be due in part to differences in fuel density. The H/CNG fuel contained approximately 86% of the energy as the CNG, 776 versus 905 Btu/ft³ (see Appendix B: Fuel Properties). The higher energy density of CNG enabled the CNG buses to travel farther before returning to base, so the CNG vehicles were dispatched for longer periods and accumulated more mileage. In addition to the fuel density difference, energy equivalent fuel economy may also have affected the mileage accumulation (see Fuel Economy section below).

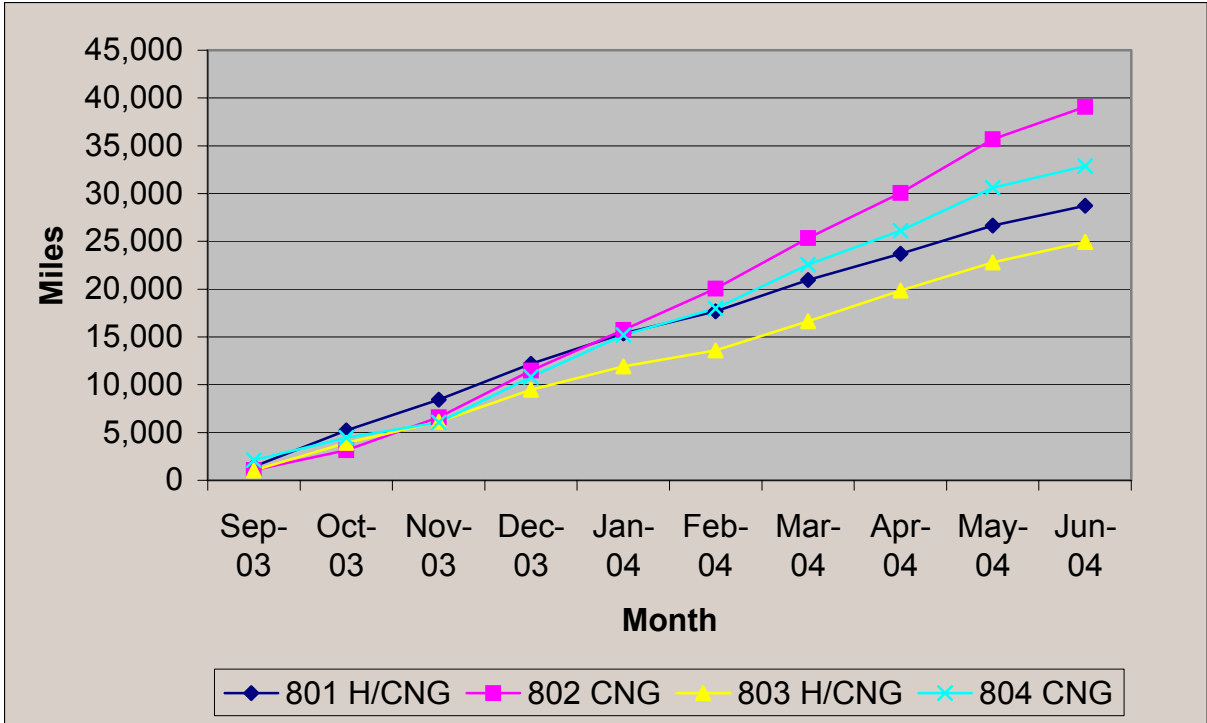


Figure 5: Accumulated Mileage by Vehicle

Fuel Economy

Daily fuel logs were used to record fuel use and mileage between fueling intervals. Vehicle fuel economy can be derived from these data and are presented here on a diesel gallon equivalent (DGE) energy basis. Table 6 summarizes the energy content and energy equivalence of several different fuels based on their thermal energy content.

Table 6: Energy Content and Diesel Fuel Equivalence

Fuel	Lower Heating Value	Diesel Fuel Equivalence	Source
Diesel #2	128,980 Btu/gal	1.00 gal	Dickson, Woodward, "Diesel Fuel Oils," NIPER-172PPS, October 1991
Diesel #1	125,780 Btu/gal	1.03 gal	"Thermal Properties of Petroleum Products" Government Printing Office, 1992
Liquefied Natural Gas	78,000 Btu/gal	1.65 gal	Perry's Chemical Engineering Handbook, 5th ed. 1973
Compressed Natural Gas	906 Btu/scf	142.36 scf	SunLine fuel analyzed by Quantum Analytical Services, Inc.*
H/CNG (20/80 volume %) blend	777 Btu/scf	166.00 scf	SunLine fuel analyzed by Quantum Analytical Services, Inc.*

*See fuel properties in Appendix B.

The fuel economy of the four buses ranged from 3.37 miles per DGE for H/CNG bus #803 to 4.25 miles per DGE for CNG bus #804. Figure 6 shows the fuel economy for all vehicles during the in-use assessment period. The average CNG fuel economy was 4.13 miles per DGE compared to an average H/CNG fuel economy of 3.62 miles per DGE. This is a 12.3% fuel economy reduction based on the in-use data. Chassis dynamometer emission testing, later in the project, indicated fuel consumption penalties for H/CNG buses of 10% and 14% on different test schedules. The in-use and dynamometer fuel consumption of the H/CNG buses fall short on the project objective of fuel consumption parity with the CNG buses, in spite of the fact that equivalent fuel economy was obtained in the laboratory engine dynamometer tests. Clearly additional refinement of the H/CNG engine calibration beyond what can be done in a limited set of steady state engine tests is required. Additional calibration could be directed at obtaining CNG equivalent fuel economy with lower NO_x emissions, or CNG equivalent NO_x emissions but with better fuel economy.

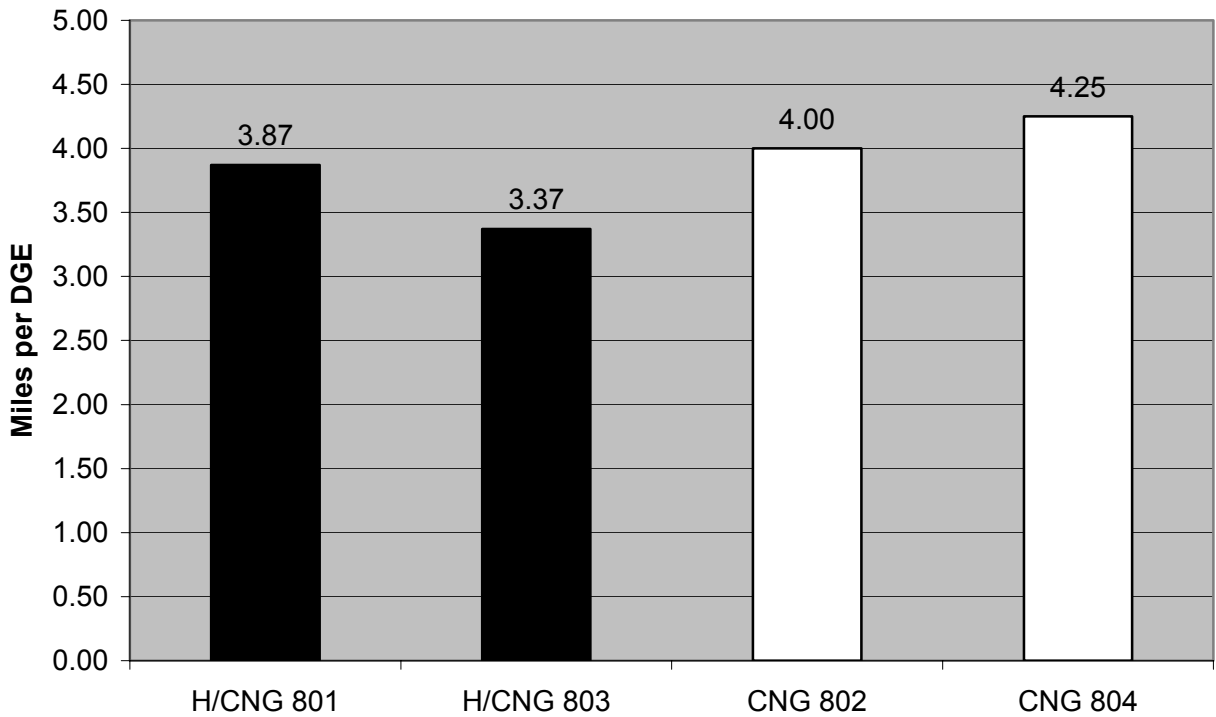


Figure 6: In-service Fuel Economy

Days In Service

The in-service assessment and data collection period totaled 271 days. Maintenance records and daily fuel logs were analyzed to assess the actual number of days the test vehicles were operated during this period, which indicates the degree of in-service reliability (Table 7).

Table 7: Daily Vehicle Operation Summary

	H/CNG 801	H/CNG 803	CNG 802	CNG 804
Days in Data Collection Period	271	271	271	271
Actual Days of Bus Operation	240	241	229	227
Percentage of Days Bus Operated	88.6%	88.9%	84.5%	83.8%

On average, the four test vehicles operated approximately 86.5% of the available time. The CNG vehicles averaged 84.2%, and the H/CNG vehicles averaged 88.8%. Although the H/CNG buses operated a higher percentage of the time than the CNG buses, the CNG vehicles accumulated more miles during this period. The additional mileage accumulated by the CNG vehicles dictated additional scheduled maintenance and in some cases negatively impacted the days of operation. Still, it is encouraging that the H/CNG vehicles operated more than 85% of the time, essentially the same reliability as attained by the CNG vehicles.

Chassis Dynamometer Emissions Testing

Test Schedules

West Virginia University (WVU) characterized the exhaust emissions of the H/CNG and CNG vehicles using their mobile laboratory. Exhaust emissions were analyzed on two different test schedules—the Orange County Transit Authority cycle (OCTA) and the City-Suburban Heavy Vehicle Route (CSHVR). These test schedules were chosen as being the most representative of the SunLine Transit routes. The OCTA cycle shown in Figure 7 is a speed versus time schedule. The cycle was developed based on in-service data logged from Orange County, CA transit buses. The cycle has an average speed of 12.3 mph and a maximum speed of 41 mph. In this project, double length OCTA cycles were used to improve the accuracy of the PM measurements by increasing the mass of particulate matter collected on the filter media. The CSHVR shown in Figure 8 is a speed versus distance test. The distance-specific route ensures that a vehicle employs full power during the test with free accelerations and travels the prescribed distance. The CSHVR covers a distance of 6.67 miles with a maximum speed of 44 mph.

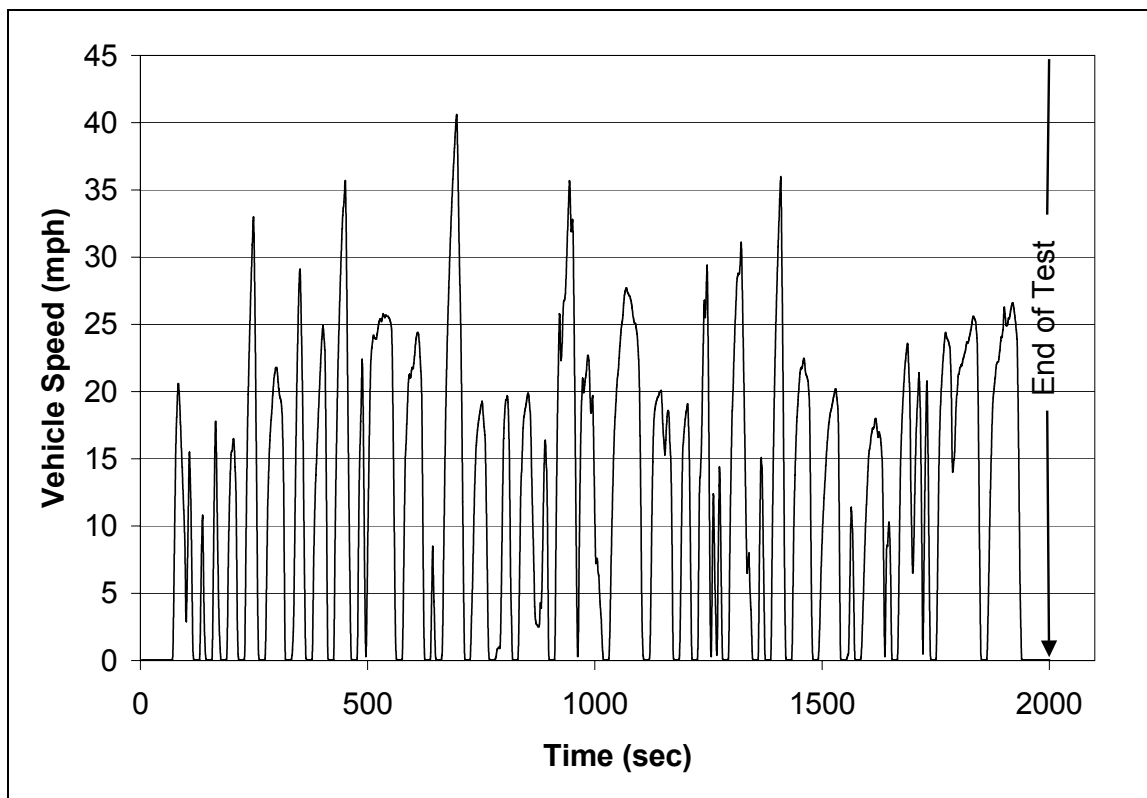


Figure 7: Orange County Transit Authority Cycle.

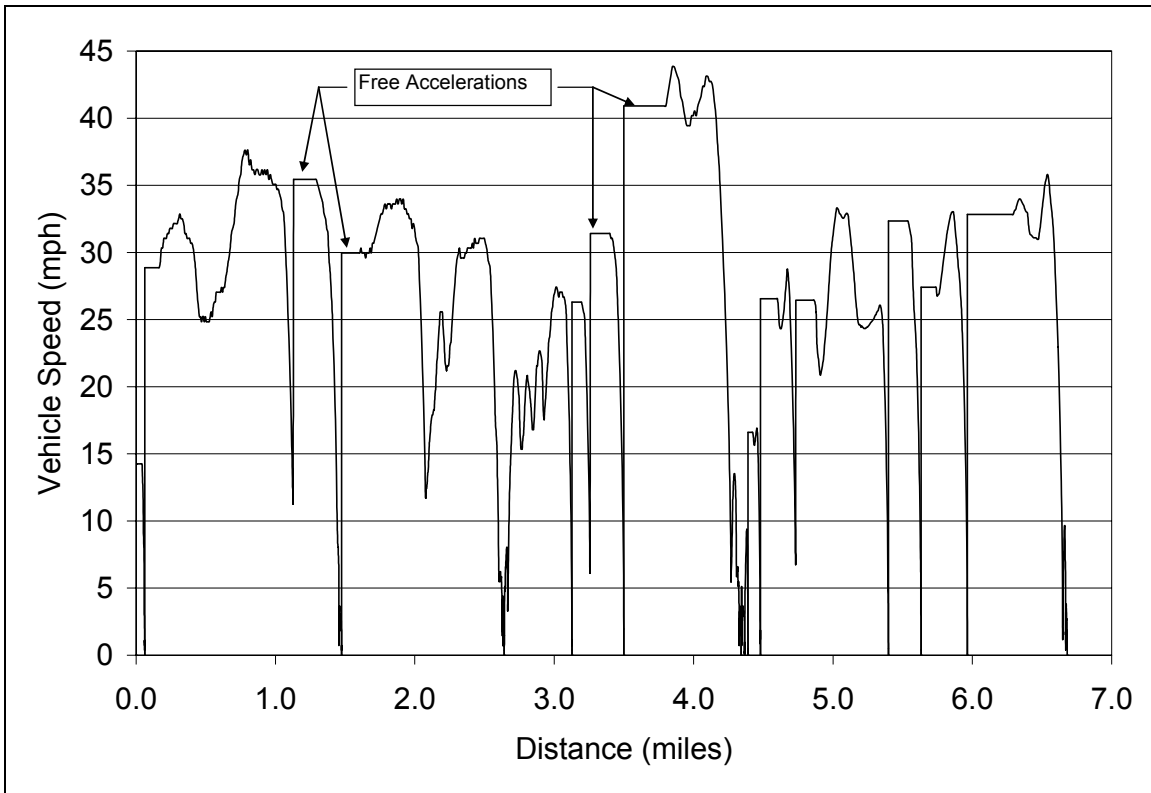


Figure 8: City Suburban Heavy Vehicle Route.

Data Analysis

Emissions of NO_x, PM, NMHC, and CO as well as methane (CH₄) were measured over the test schedules. Test results are an average of three replicate tests and are shown in Tables 8 and 9 for the CSHVR and OCTA test schedules respectively. The same emission measurements are presented graphically in Figures 9 through 12. These figures also show the maximum and minimum emission values and indicate excellent repeatability for NO_x and hydrocarbons. Repeatability for PM and CO is not as good because of the extremely low values measured.

Table 8: Emission measurements for the CSHVR in grams/mile.

Pollutant	Bus 801 (H/CNG)	Bus 803 (H/CNG)	Bus 802 (CNG)	Bus 804 (CNG)
NO _x	3.8	3.4	8.2	8.2
PM	0.005	0.015	0.010	0.005
NMHC	0.22	0.35	0.34	0.49
CO	BDL ¹	0.08 ²	BDL	BDL
CH ₄	11.34	13.21	11.62	17.27

¹ BDL means Below Detection Limit

² Measured result of one test run, two other test runs were BDL

Table 9: Emission measurements for the OCTA2X in grams/mile.

Pollutant	Bus 801 (H/CNG)	Bus 803 (H/CNG)	Bus 802 (CNG)	Bus 804 (CNG)
NO _x	5.5	3.7	11.5	10.0
PM	0.007	0.004	0.006	0.006
NMHC	0.49	0.61	0.40	0.57
CO	BDL	0.05	BDL	0.17 ³
CH ₄	14.03	18.41	14.42	19.09

³ Average result of two test runs, third test run was BDL

The H/CNG fueled buses demonstrated a reduction in NO_x of more than 50% compared to the CNG buses; 56% lower on the CSHVR and 57% lower on the OCTA2X cycle (Figure 9). These reductions are attributed to the leaner air-to-fuel ratio and retarded spark-timing of the H/CNG buses.

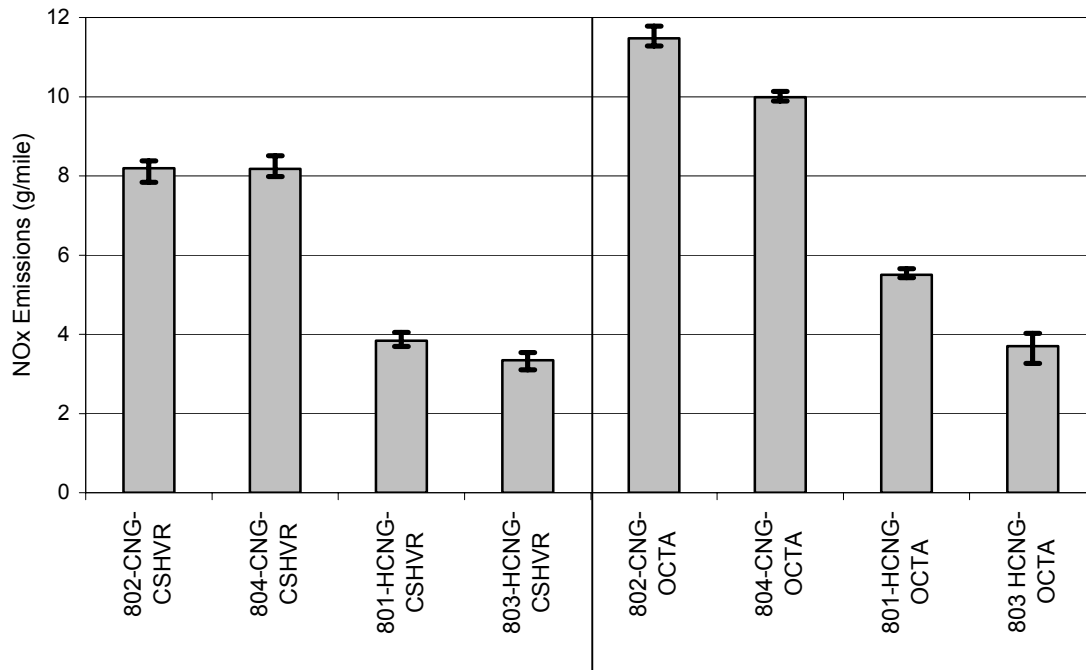


Figure 9: NO_x emission results by bus number and test schedule (bars denote minimum and maximum test results).

The CSHVR test schedule produced more highly variable PM results than observed in the OCTA test schedule results (Figure 10). Both H/CNG and CNG buses had very low PM emissions; no discernable difference between fuel types is apparent from these tests.

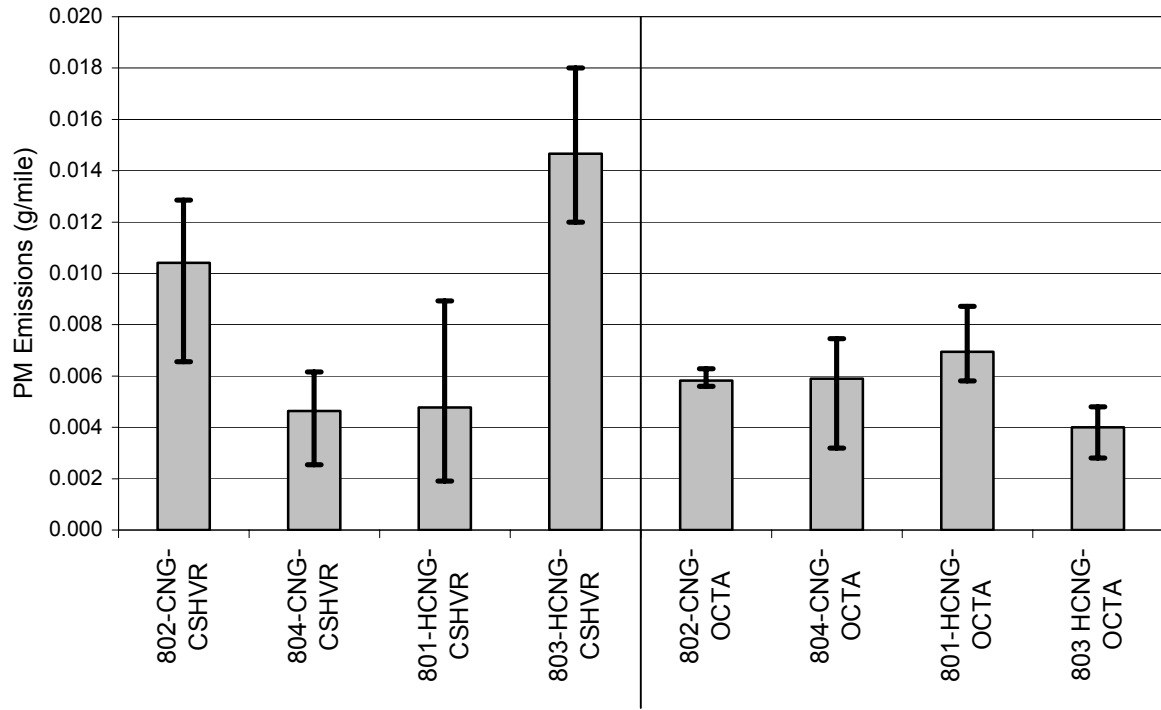


Figure 10: PM emission results by bus number and test schedule (bars denote minimum and maximum test results).

The hydrocarbon emissions for H/CNG and CNG are slightly increased on the OCTA test schedule relative to the CSHVR (Figure 11). The very low NMHC emissions indicate the oxidation catalysts worked well. No discernable difference between fuel types is apparent from these tests.

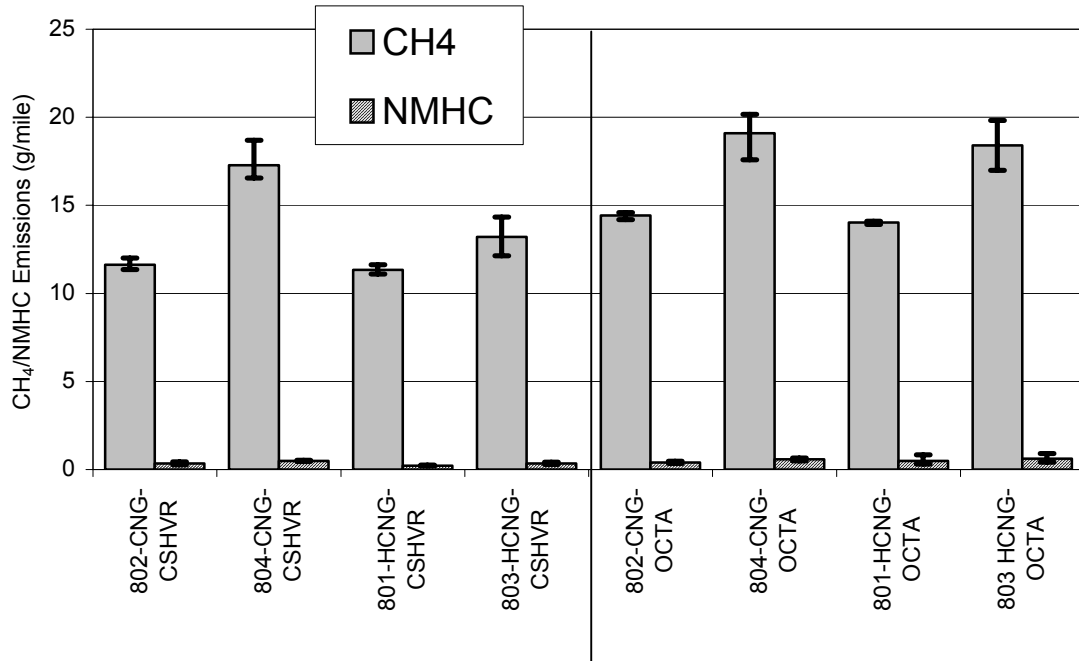


Figure 11: Hydrocarbon emission results by bus number and test schedule (bars denote minimum and maximum test results).

The CO measurements were below detectable limits for most of the test runs on both test schedules (Figure 12). The detectable measurements obtained were very low and indicate the oxidation catalyst is performing well. No discernable difference between fuel types is apparent from these tests.

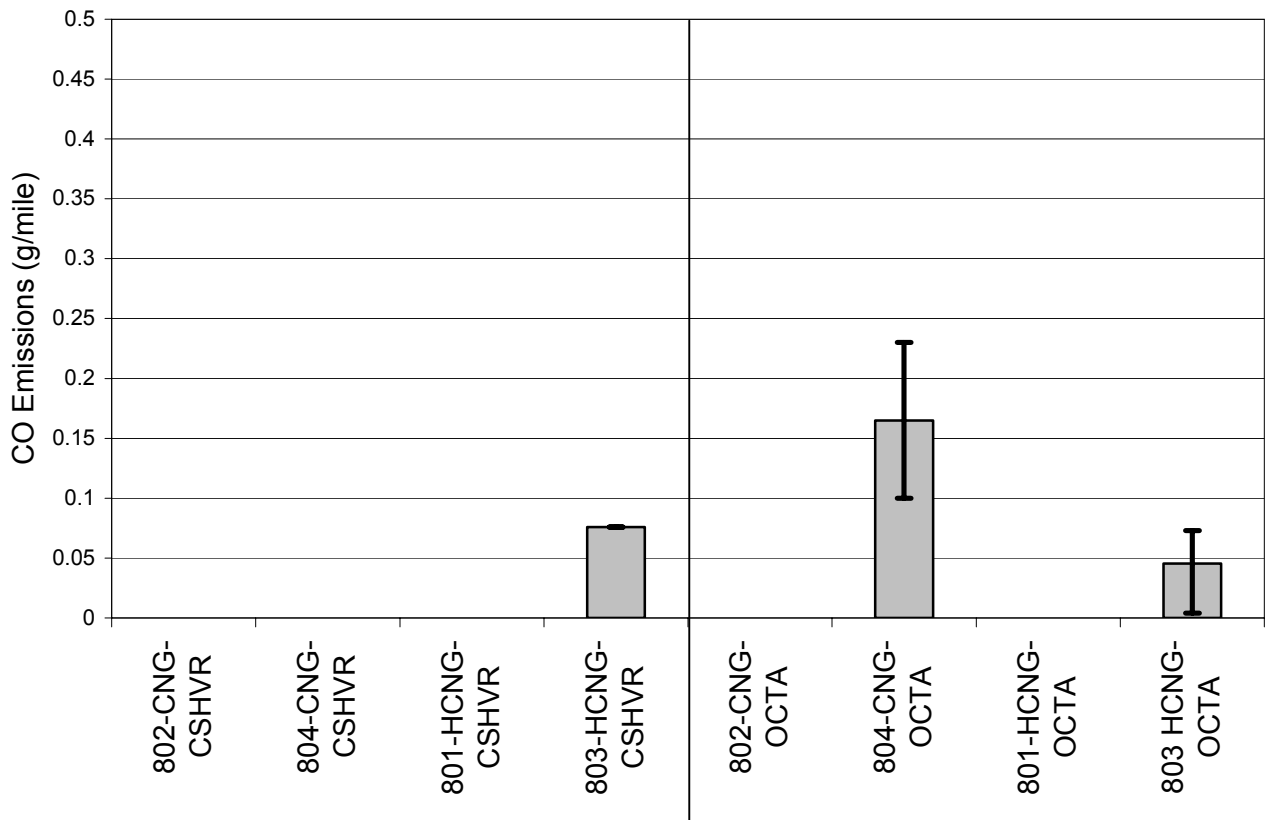


Figure 12: CO emission results by bus number and test schedule (bars denote minimum and maximum test results).

Final Engine and Vehicle Inspection

Engine analysis and vehicle inspection were conducted at 24,000 miles to compare engine wear, fuel system wear, and other metrics to illuminate differences between the CNG and H/CNG test buses. The following is a list of parameters evaluated and recorded:

Engine Analysis: including stall-speed tests, spark-plug replacement frequency, engine compression tests, and borescope inspections

Fuel System Analysis: including high and low pressure regulators

Oil Analysis: was performed at each preventive maintenance interval

Engine Checks

Stall Speed Testing

Stall speed tests are used by SunLine to quickly assess overall and engine subsystem performance. With the brakes engaged and wheel chocks in place, the bus is put into gear and the accelerator pedal is depressed. In this situation, technicians can determine several key operating parameters including turbo pressure, fuel pressure, and proper fuel mixing.

For overall engine performance, the accelerator position is increased until the engine is stalled. The higher the engine speed attained the better. In general, buses with engine stall speeds above 2000 rpm operate acceptably. Stall speed tests were performed on all test buses after 24,000 miles and are shown in Table 10.

Table 10: Stall Speed Test Results

	H/CNG Engine		CNG Engine	
	Bus 801	Bus 803	Bus 802	Bus 804
Stall Speed (RPM)	2460	2500	2610	2650

Spark Plug Replacements

Spark plug replacement intervals were assessed after 24,000 miles. The average miles between spark plug replacements for each bus are shown in Table 11.

Table 11: Spark Plug Replacement Intervals

	H/CNG Engine		CNG Engine	
	Bus 801	Bus 803	Bus 802	Bus 804
Miles between spark plug changes	8414	5836	10195	3082
	7923	9024	10154	3929
	10920	6787		3346
Average	9085	7215	10174	3452

Records for buses 801, 802, and 803 indicate the average interval between plug changes was around 8,000 miles. Bus 804 shows considerably fewer miles between changes and appears to be missing some records. The recommended change interval from CWI is 18,000 miles. Further assessment for the high frequency of spark plug changes was not conclusive but indicates the changes may not have been necessary.

SunLine Transit maintains and operates around 60 CNG buses. All of these buses with the exception of the four buses in this project are older generation technology. The buses in this project were all upgraded to the latest (B Gas Plus) technology including coil-on-plug, which eliminates standard spark plug wires. With the coil-on-plug technology, technicians could no longer assess spark plug quality via the spark plug wires as practiced on the rest of the fleet. Therefore if a driver made note of an abnormal idle condition and there were no service lights or fault codes for the technician to read, on some occasions a new set of spark plugs was installed. Subsequently, a training update was provided to alert the technicians to premature changes and the in-use spark plug intervals are being reassessed.

Engine Cylinder Compression

Engine cylinder compression checks were performed on the test bus engines. A Matco® compression tester model CP-166K was connected to the cylinder through the spark plug bore while the engine was cranked at 250 rpm. The allowable cylinder compression limits for the B Gas Plus engines are 15.8 bar (230 psi) and 19.3 bar (280 psi). In addition, there should not be more than a 15% difference between the maximum and minimum readings

from cylinder to cylinder. As shown in Table 12, all bus engines except for bus 804 were well within these limits.

Table 12: Engine Compression Measurements (bar)

	H/CNG Engine		CNG Engine	
	Bus 801	Bus 803	Bus 802	Bus 804
Cylinder 1	19.5	19.5	18.0	18.5
Cylinder 2	18.5	19.5	18.5	18.0
Cylinder 3	19.5	19.5	19.0	18.5
Cylinder 4	19.0	19.5	19.0	15.5
Cylinder 5	19.5	19.5	19.2	19.0
Cylinder 6	18.5	19.0	19.0	19.0
Difference	5.1%	2.6%	6.3%	18.4%

The engine compression check for CNG bus 804 measured over 18% difference between the maximum and minimum readings. A cylinder leak down test was performed and confirmed a leak on cylinder 4. A cylinder bore scope evaluation, discussed in the next section, identified a slight oil leak past the valve guide seal along with carbon deposits on the valve stem and seat. Typically oil leaks from around a valve guide will cause carbon deposits to form on the valve stem and then eventually form on the face and the seat of the valve. These deposits will result in compression loss and over time poor performance. The cylinder head was removed and upon further inspection a crack was discovered at the edge of the valve seat. There were no engine or vehicle inspections performed on the test vehicles prior to the project. Therefore, it is difficult to assess when the crack occurred. This event was considered an anomaly and the cylinder head was replaced. The compression test was repeated with the new head and the difference between the maximum and minimum cylinder readings was 1.5%.

Borescope Inspection

A visual inspection of the engine combustion chambers was performed on all four engines with the use of an ITI model 123500 and Cornwell Tools flexible borescopes. Due to interference with chassis components cylinders 1, 2, and 3 were inspected using the flexible borescope. This device allows technicians a plan view of the cylinder bore and piston bowl. Cylinders 4, 5, and 6 were inspected with the ITI borescope. In addition to a plan view of the cylinder bore, this device allows the technicians a full 360° perpendicular view of the cylinder wall. This device can also provide inspection of the valves, valve guide seals, and valve seats.

The SunLine mechanics and technicians could not observe any difference between the CNG and H/CNG combustion chambers. All the borescope inspections appeared normal with the exception of bus 804, cylinder 4 as noted above.

Fuel System

High-Pressure Gas Regulator

All of the Thomas buses in the SunLine fleet were originally equipped with high-pressure regulators manufactured by GFI. Subsequently the GFI regulators and rebuild kits were no longer manufactured. Standard procedure for SunLine technicians is to replace failed GFI units with high-pressure regulators manufactured by Tescom. Regulator outlet pressure was assessed at preventive maintenance intervals and at 24,000 miles. The high-pressure threshold is 95 psig. When an outlet pressure exceeded the threshold, the pressure regulator was replaced or rebuilt. The original GFI high-pressure regulator on bus 801 was replaced with a Tescom model during a preventative maintenance check. At 24,000 miles all high-pressure regulators were within specification.

Low Pressure Gas Regulator

Low-pressure gas regulators are specified and installed on the engine by CWI. Since one engine was new and the other three were upgraded to the current Plus technology, all four buses started the project with new low-pressure regulators. The specified operating tolerance from CWI is between 35 and 55 psig. During the 24,000 mile test period all four buses were within the specified range when checked. The project team did however elect to replace the low-pressure regulator in bus 803. While this pressure regulator was operating within tolerance, at 38 psig, it was replaced prior to the exhaust emission testing.

Oil Analysis

Oil analysis was conducted with each oil change at 6,000-mile intervals. The analysis performed by Analyst, Inc. assessed component wear by looking for specific materials in the lube oil. A report is provided to SunLine's maintenance department if there are any excess wear metals or unusual contamination. No significant problems or concerns were observed in the oil analyses. All buses were in the normal range of wear metals for the CNG and H/CNG buses.

Findings and Recommendations

This project demonstrated that with minor engine and vehicle modifications the 20/80 H/CNG blend can be used in revenue service fleets with similar operational performance as CNG. Specific findings include:

- Minor engine and vehicle hardware modifications were required for the 20/80 H/CNG operation; a new fuel mass flow rate sensor and additional vehicle fuel tanks.
- All four test vehicles surpassed 24,000 in-service miles-- CNG buses accumulated a total of 71,951 miles: 39,088 for bus 802 and 32,863 for bus 804, H/CNG buses accumulated a total of 53,681 miles: 28,723 for bus 801 and 24,958 for bus 803.
- The H/CNG fuel contained approximately 86% of the energy as the CNG, 776 versus 905 Btu/ft³ (see Appendix B: Fuel Properties).

- On average, the four test vehicles operated approximately 86% of the available time. There was no significant difference in the availability of the CNG and H/CNG buses.
- The 20/80 H/CNG blend reduced NO_x emissions by over 50% relative to the CNG control buses. There was no discernable difference in PM emissions for the two fuels. Emissions of NMHC and CO were near detection limits.
- A fuel economy penalty was experienced in the operation of the H/CNG blend; in-use fuel economy for the H/CNG buses was reduced by about 12% relative to the CNG operation on a diesel gallon equivalent basis.
- The 24,000-mile engine and vehicle inspection did not indicate any impact due to the use of H/CNG fuel.

Specific recommendations resulting from this project include:

- In order to evaluate the long-term effect of H/CNG blends on the engine, a follow-on study should include a much longer quantitative assessment of maintenance costs relative to CNG, followed by a complete engine teardown. Comparative 1000-hour engine dynamometer durability with complete engine teardown would also be useful.
- Further testing and development should include an optimization of the H/CNG engine calibration for fuel economy with NO_x emission parity relative to CNG.
- Future fleet evaluation should include more detailed reporting of oil analysis results.

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Appendix A: Tank Temperature Report

Tank-temp Report

from

Hydrogen Components Incorporated

By Frank Lynch
November 2003

Purpose

We know that 20% hydrogen in CNG will increase the maximum gas temperature observed toward the end of refueling, relative to pure CNG refueling. We want to be sure that the tank is not heated past the manufacturer’s maximum recommended temperature (85°C, 185°F), even on the hottest of days at SunLine (49°C, 120°F).

Experimental Setup

The hottest place in a compressed gas cylinder during filling is near the opposite end from where the gas enters, also known as the “butt” end of the tank. This is true because the gas entering the tank is relatively cool. The gas that is already in the tank is heated by compression and eventually transfers some of this heat into the cooler incoming gas. The butt end of the tank is furthest from the cool incoming gas and, therefore, the hottest part of the tank.

A 1 foot (30 cm) long stainless steel temperature probe (HCI Model AP-1TP, see Figure 1) was inserted into the butt end of the tank through the end plug. Inside the probe is a pair of National Semiconductor LM335AZ temperature sensor ICs that produce 10 microvolts per Kelvin. Kelvin temperatures are converted into more familiar °C by subtracting 273.15.



Figure 1. HCI Model AP-1TP high pressure gas tank temperature probe

We stuck an identical temperature sensor IC to the outer surface of the tank with a little insulation over it to reduce cooling by the ambient air.

The bus fuel gauge is a 1-5 volt 0-3000 psig transducer. We used it to monitor pressure during refueling.

The pressure and temperature signals were monitored by a PLC (12-bit A/D converter) and sent via serial cable to a laptop computer in terminal mode at 1 second intervals.

Test Results

Figure 2 shows the pressure and temperature variations during the refueling of a Hythane® bus. The initial pressure in the tank 1.72 MPa (250 psi) was barely enough to operate the bus. Starting with surface and core temperatures in the low 30s Celsius (high 80s F), temperatures rose steadily until the dispenser unexpectedly stopped at 517 seconds. Repairs were completed by 877 seconds and refueling resumed. During the delay, the tank core temperature fell 4°C (7 °F). The tank surface did not cool significantly during this 6 minute period.

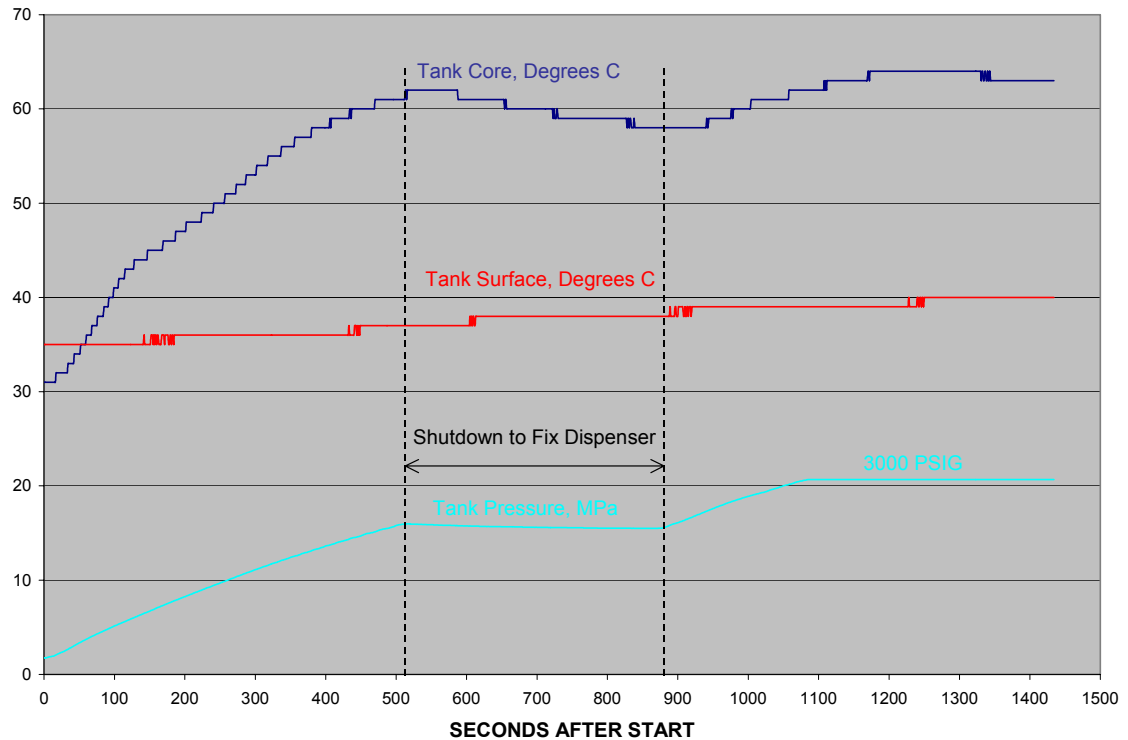


Figure 2. Bus tank pressure and temperature data during refueling with Hythane®.

Refueling was complete at 1086 seconds. Without the 6 minute delay to repair the dispenser, the refueling period would have been 726 seconds or 12.1 minutes. The maximum temperature observed at the core of the tank was 64°C. The maximum surface temperature was 40°C.

This test was not conducted on the hottest of days at SunLine. We also had a 6 minute shutdown that allowed the tank core to cool by 4°C (7°F). Next, we will estimate worst case conditions heating conditions on a hot day at SunLine.

Extrapolated Worst Case Tank Heating

The test data were taken on a day when ambient temperature was in the low 30s Celsius (high 80s F). It gets much hotter than this at SunLine in mid-summer. We also had a 6 minute interruption when the dispenser shutdown. During the interruption, the tank core temperature fell by 4°C (7°F). Figure 3 extrapolates the test results to a 49°C (120°F) starting temperature (hot day at SunLine) without the cooling during the dispenser repairs.

The maximum tank core temperature would reach 86°C (187°F) under these conditions. This is not a problem, even though it exceeds the tank manufacturer’s tank temperature recommendation. We know that the inner surface of the tank is cooler than the core gas temperature.

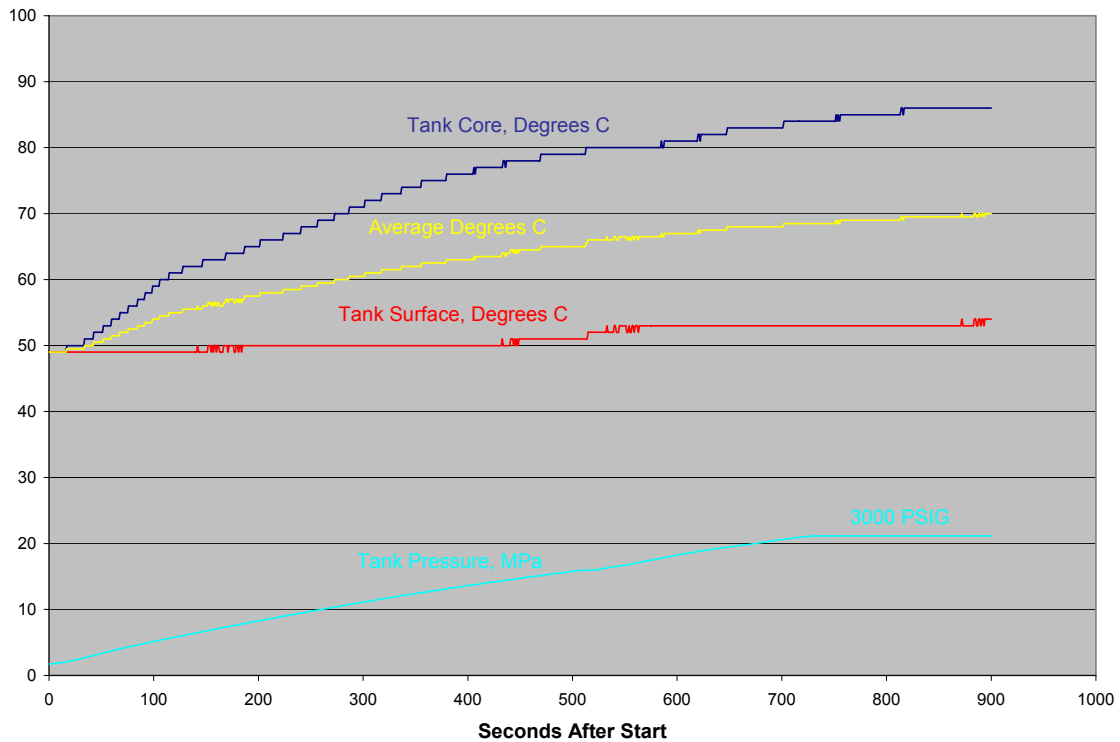


Figure 3. Extrapolated pressure-temperature data for a hot day at SunLine

During refueling of pure hydrogen buses at Chicago Transit Authority, HCI needed to know the average gas temperature to provide a temperature-compensated filling pressure for the fuel cell buses. We used temperature instruments identical to those used at SunLine—a probe at the tank core and a tank surface temperature sensor. The unexpected result of watching these two temperatures come to equilibrium after a rapid refueling was

that a raw average of the two temperatures was the average gas temperature at the end of refueling.

We know that the inner surface of the tank is cooler than the average gas temperature, 70°C (158°F) maximum in Figure 3. Therefore, the maximum core temperature exceeding 85°C (185°F) is not a problem. No part of the tank reaches that temperature. Nor does any part of the tank reach the average gas temperature—well below the manufacturer’s limit in Figure 3.

Comparison to Natural Gas

There was an error in recording the data for a comparable natural gas refueling. From memory of the data on the computer screen, the peak temperature was about 10°C lower than Figure 2. The tank outer surface was 1°C cooler.

Conclusions

Refueling of 20.7 MPa (3000 psi) tanks with 20 volume percent hydrogen in compressed natural gas cannot heat the tank materials to their limit (85°C, 185°F), even when ambient temperature rises to 49°C (120°F). Under such hot refueling conditions the peak gas temperature could exceed 85° (185°F). We know that the tank materials are cooler than the gas at the core of the tank.

We further know that the tank materials do not reach the average gas temperature. Extrapolating our test results to a refueling that begins with the tanks at 49°C (120°F), We project that the average gas temperature rises to 70°C (158°F)—comfortably below the limit on tank temperature.

These results are specific to natural gas containing 0-20% hydrogen by volume. Greater concentrations of hydrogen will cause further heating. Additional testing should be performed if greater concentrations of hydrogen are used.

Appendix B: Fuel Properties

Quantum

Analytical Services Inc.

www.quantumairlab.com

1210 E. 223rd Street, Suite #314 • Carson, California 90745 • 310/830-2226 • Fax 310/830-2227

CLIENT: Sunline Services Group
 LABORATORY NO: 04-079, 04-083, 04-090

Laboratory Analysis Report Analysis Method: ASTM3588

Analyte, Units	Sample ID	Unit 802	Unit 804	Unit 803	Unit 801
	Sample Date	02/09/04	01/10/04	02/12/04	02/12/04
	Analysis Date	02/09/04	02/10/04	02/13/04	02/13/04
	Report Date	02/10/04	02/10/04	02/16/04	02/16/04
	Lab ID	04004-15	04104-10	04304-7	04304-8
	Units	Mole %	Mole %	Mole %	Mole %
Methane, %		97.4	97.4	77.3	77.6
Ethane, %		0.96	0.91	0.79	0.71
Ethylene, %		<0.1	<0.1	<0.1	<0.1
Propane, %		0.18	0.20	0.16	0.14
Propylene, %		<0.1	<0.1	<0.1	<0.1
i-Butane, %		<0.1	<0.1	<0.1	<0.1
n-Butane, %		<0.1	<0.1	<0.1	<0.1
1-Butene, %		<0.1	<0.1	<0.1	<0.1
i-Butylene, %		<0.1	<0.1	<0.1	<0.1
Trans-2-Butene, %		<0.1	<0.1	<0.1	<0.1
cis-2-Butene, %		<0.1	<0.1	<0.1	<0.1
i-Pentane, %		<0.1	<0.1	<0.1	<0.1
n-Pentane, %		<0.1	<0.1	<0.1	<0.1
1-Pentene, %		<0.1	<0.1	<0.1	<0.1
2,2-Dimethyl Butane, %		<0.1	<0.1	<0.1	<0.1
2,3-Dimethyl Butane, %		<0.1	<0.1	<0.1	<0.1
2-Methyl Pentane, %		<0.1	<0.1	<0.1	<0.1
3-Methyl Pentane, %		<0.1	<0.1	<0.1	<0.1
n-Hexane, %		<0.1	<0.1	<0.1	<0.1
1-Hexene, %		<0.1	<0.1	<0.1	<0.1
C6+, %		<0.1	<0.1	<0.1	<0.1
CO ₂ , %		1.4	1.47	1.1	1.1
CO, %		<0.1	<0.1	<0.1	<0.1
O ₂ , %		<0.1	<0.1	<0.1	<0.1
N ₂ , %		<0.1	<0.1	<0.1	<0.1
H ₂ , %		<0.1	<0.1	20.7	20.4
H ₂ S, %		<0.1	<0.1	<0.1	<0.1
Average Molecular Weight		16.660	16.637	13.604	13.646
Total Wt.% Adjusted Sp. Gravity		0.5746	0.5738	0.4692	0.4707
Compressibility Factor (14.696 psi, 60F)		0.9979	0.9979	0.9984	0.9984
NET BTU/FT ³		907	905	776	777
GROSS BTU/FT ³		1007	1005	866	866

CHONS	wt%	wt%	wt%	wt%
Carbon	73.2	73.1	71.0	71.0
Hydrogen	24.0	24.0	26.4	26.3
Oxygen	2.8	2.8	2.5	2.7
Nitrogen	<0.1	<0.1	<0.1	<0.1
Sulfur	<0.1	<0.1	<0.1	<0.1
Dry F Factor (60F, 1 atm)	8294	8594	8387	8391
SDFC/MMBTU, ASTM 3588				

REPORT DOCUMENTATION PAGE

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