Heavy-Duty Truck Demonstration with a 400-HP DDC Series 60G LNG Engine, and Support for the Downtown Los Angeles LNG Station

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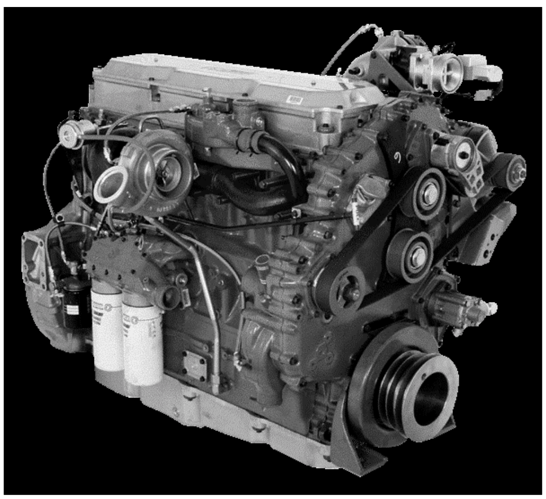

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P R E P A R E D   F O R

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400-HP DDC Series 60G LNG Heavy-Duty Truck Demonstration

Final Report FR-99-104

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Date:

9 June 2000

Disclaimer

Special Note

Ownership / Name Change to Arthur D. Little, Inc. from ARCADIS Geraghty & Miller, Inc.

Effective January 22, 2000, the Transportation Technology group of ARCADIS Geraghty & Miller was purchased by Arthur D. Little, Inc. Thus, work performed by the prime contractor in this project was initiated under ARCADIS Geraghty & Miller and completed under Arthur D. Little, Inc. However, nearly all the work for the project was performed under the name of ARCADIS Geraghty & Miller. For simplicity, ARCADIS Geraghty & Miller is referred to solely as the prime contractor in this report.

ACKNOWLEDGMENTS

ARCADIS Geraghty & Miller wishes to thank the following individuals for their valuable contributions to this project:

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1. EXECUTIVE SUMMARY

1.1 PROJECT BACKGROUND

Among on-road motor vehicles, Diesel-fueled heavy-duty trucks emit disproportionately high amounts of oxides of Nitrogen (NO_x) and particulate matter (PM). The trucking industry has taken an active interest in the use of engines powered by liquefied natural gas (LNG) to reduce NOx and PM emissions. However, major barriers exist to widespread use of LNG in trucking applications, including reduced performance and higher initial capital costs compared to diesel-fueled vehicles, as well as a limited fueling infrastructure.

To help address these barriers, the National Renewable Energy Laboratory (NREL), with funding from the U.S. Department of Energy, joined with the South Coast Air Quality Management District (SCAQMD) to contract with a team led by the San Jose Transportation Technology Group[1] of ARCADIS Geraghty & Miller.[2] The focus of the contract was to upgrade a Detroit Diesel Corporation (DDC) Series 60G (S60G) engine for increased power and torque, and demonstrate this engine in an LNG-fueled semi-tractor. The project's complete objectives are described below.

1.2 OBJECTIVES

The primary objectives of this project were to:

1. Develop and demonstrate a low-emission, high performance LNG tractor in a Class 8 trucking application.
2. Cost share two additional Series 60G-equipped LNG tractors under a sister project primarily funded by the California Energy Commission.
3. Achieve California emissions certification of the upgraded DDC S60G engine for Class 8 trucking applications, and obtain chassis dynamometer emissions test data as well, if possible.
4. Extend the period of operation for the downtown Los Angeles LNG fueling station for approximately one year, through direct financial support.
5. Document project results in Monthly Progress Reports and a Final Report.

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[1] This group consists of staff in the Mountain View and Fullerton offices in California, and is part of the group formerly known as Acurex Environmental.
[2] On January 22, 2000, ARCADIS Geraghty & Miller's Transportation Technology Group became part of Arthur D. Little, Inc. (see box on page ii).

1.3 SPONSORSHIP AND PARTICIPANTS

Direct funding for this project was provided by the South Coast Air Quality Management District (SCAQMD) and the U.S. Department of Energy (DOE) through the National Renewable Energy Laboratory (NREL). ARCADIS Geraghty & Miller served as the prime contractor. Under contract #ACI-6-16627-01 with ARCADIS Geraghty & Miller, NREL primarily sponsored Task 0. Tasks 1-4 were sponsored by SCAQMD under contract #98068. Table 1-1 lists the subcontractors used by ARCADIS Geraghty & Miller, and the functions they served in the project.

Table 1-1. Project subcontractors and their roles.

Subcontractor	Primary Role / Function
Detroit Diesel Corporation (DDC)	Engine and vehicle upgrades, and field support
Valley Detroit Diesel Allison (VDDA)	Subcontractor to DDC, assist with above tasks
Jack B. Kelley, Inc. (JBK)	Vehicle operation, maintenance and data collection
Cryogenics Research & Development	Lease of Downtown LNG station equipment
Mesa Pacific LNG	Lease of Downtown LNG station land; station operation

1.4 OVERVIEW OF TECHNOLOGY AND PROJECT PARAMETERS

As Table 1-2 indicates, the vehicle selected for this demonstration was a 1994 Freightliner FLD 120, a Class 8 long-hood conventional semi-tractor with a tandem rear axle. It was one of five trucks that were factory-equipped in late 1994 with LNG fuel systems and the first prototype version of the DDC Series 60G. After JBK purchased this vehicle and two others, DDC and VDDA performed the engine upgrade on Tractor #1. (About 10 months later two more engine upgrades were performed under CEC funding, with cost sharing by SCAQMD – see 3.2.7). The upgrade involved modifications to the cylinders and liners, and to the fuel metering, ignition and engine control systems. These modifications were intended to improve the engine's emissions, fuel economy, driveability and reliability, and increase the engine's horsepower from 330 to 400 brake horsepower.

Table 1-2. Overview of the host site and key demonstration parameters.

Host Fleet	Jack B. Kelley, Inc. (JBK), Fontana, CA
Chassis	1994 Freightliner FLD 120
Engine	LNG-fueled Detroit Diesel Series 60G
Primary LNG Fueling Station Location	ALT-USA, Ontario, CA
Secondary LNG Fueling Station Locations	NGV Ecotrans, Los Angeles, CA
Location of Fleet Operating Base	Fontana, CA
Primary Use Type	Local delivery of cryogenic liquids
Primary Duty Cycle	~4 Stops / Day, Stop-and-Go, Top Speed @ 55mph
Product Hauled	Cryogenic liquids (principally liquefied nitrogen)

1.5 WORK PERFORMED AND RESULTS

Nearly all the objectives for this project were met, and several of the most important goals were exceeded. Work began in July 1998 when ARCADIS Geraghty & Miller negotiated, drafted and executed subcontracts with the host site, Jack B. Kelley (JBK), and the engine manufacturer, DDC. The engine upgrade was completed in January 1999, and the demonstration began on February 9, 1999. The tractor was deployed in the Fontana, California fleet of JBK, where it was used to haul cryogenic liquids throughout Southern California. Data gathered during its operation included fuel consumption, mileage accumulation, road calls, regular maintenance, and oil consumption. Similar data was gathered from a diesel truck for comparison.

1.5.1 Mileage Accumulation and Performance

Over the 12-month demonstration period, the tractor accumulated approximately 47,000 miles (an average of 3,900 miles per month). Throughout most of the demonstration, the tractor ran well and the driver's reports were positive. High oil consumption was documented, and found to be caused by a defect in the oil control ring in at least one cylinder. Repairs for this problem were conducted towards the very end of mileage accumulation, and took the tractor out of service for approximately eight weeks. Figure 1-1 shows the cumulative and monthly mileage for Tractor #1, and reflects this drop off in usage at the demonstration's end.

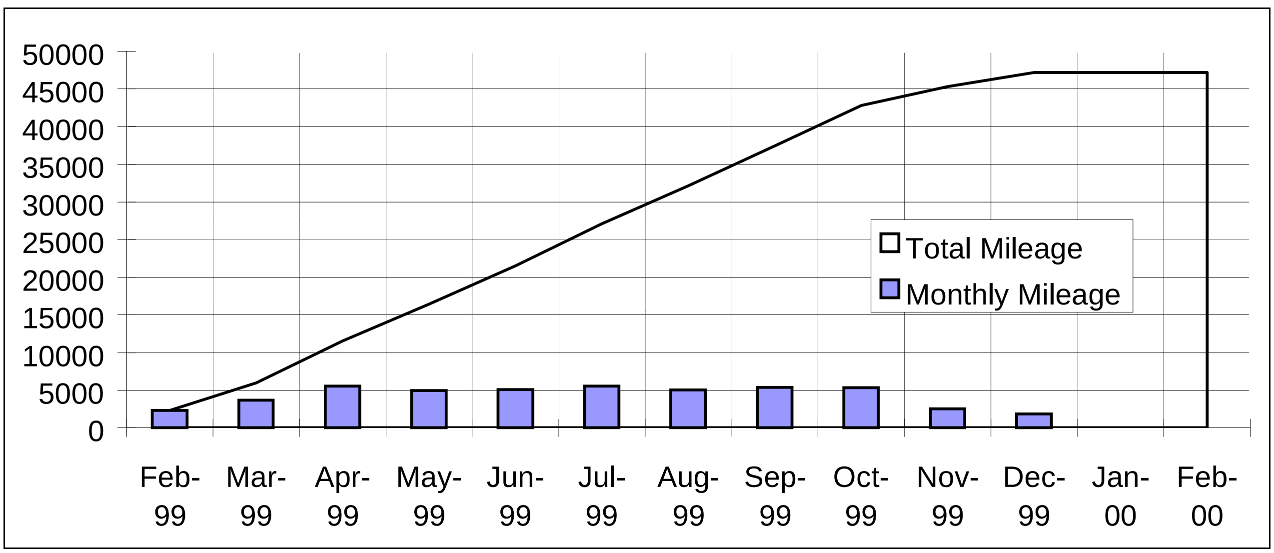

Figure 1-1 . Mileage accumulation for Tractor #1 during the 12-month demonstration.

1.5.2 Fuel Economy

The LNG tractor averaged 2.8 to 2.9 miles per gallon of LNG during its year-long accumulation of 47,000 miles. This is equivalent to approximately 4.8 miles per gallon of diesel. Figure 1-2 below shows the monthly fuel economy during the demonstration (including conversion to miles per diesel equivalent gallon (mi/DEG).

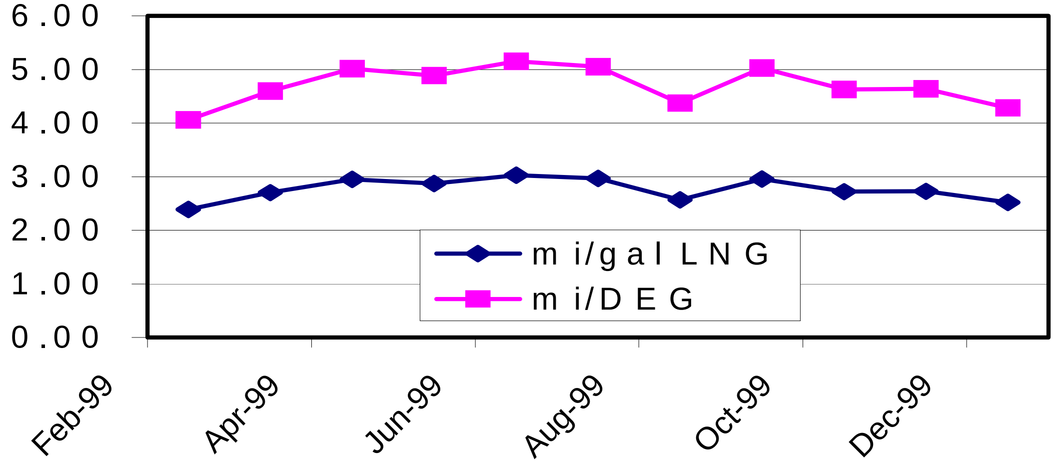

Figure 1-2. Average monthly fuel economy for Tractor #1.

1.5.3 Emissions Testing

At the writing of this report, DDC was completing certification of the upgraded high-horsepower, high-torque Series 60G engine to California's optional low-NOx emissions standard. Table 1-3 lists the results of certification testing conducted at Southwest Research Institute in January 2000. The engine will be certified to a NOx "bin" of 2.5 g/bhp-hr.

Table 1-3. Certification emissions testing results at Southwest Research Institute

Test Cycle	MAX TORQUE (lb-ft)	RATING (hp @ rpm)	NOx (g/bhp-hr)	NMHC (g/bhp-hr)	CO (g/bhp-hr)	PM (g/bhp-hr)
FTP*	1450	400@2100	1.95	0.51	1.79	0.010

*Federal Test Procedure

In addition, chassis dynamometer emissions testing was performed on one of the three LNG trucks at the Clean Air Truck Testing Services (CaTTS) laboratory in Northern California. This testing was arranged by ARCADIS Geraghty & Miller and its team, in conjunction with Pacific Gas & Electric, which paid for the testing under a separate project. Preliminary emissions data indicate that the LNG truck emitted very low levels of NOx compared to a recent model year diesel engine (see Table 1-4).

Table 1-4. Preliminary comparison of NOx emissions from diesel and LNG tractors tested
at CaTTS over the Central Business District (CBD) Test Cycle

Test Vehicle	Engine	Test Fuel	NOx (g/mi)
1986 GMC	'97 DDC Series 50	Diesel #2	27.4
1995 Freightliner FLD 120 (LNG Tractor #3)	Upgraded '95 DDC S60G	LNG	7.2
Testing for the LNG tractor was conducted at CaTTS on April 10, 2000. Testing for the diesel tractor was conducted at CaTTS on March 17, 1999. NOx data are the average of 3 tests for both vehicles. Particulate data were not yet available.			

1.5.4 Downtown LNG Station

One of the project goals was to extend operation of the Mesa Pacific LNG fueling station adjacent to NGV Ecotrans on Olympic Avenue near downtown Los Angeles. Funding from this project enabled the station to remain open for approximately 12 months beyond when it would have originally closed. It was hoped that keeping the station open longer would encourage more heavy-duty fleets to purchase LNG tractors, leading to greater demand for fuel at the station, and result in its sustained operation. However, due to high station costs and low fuel throughput (sales), the project sponsors and participants decided to close the station at the end of the period of extended operation.

1.6 CONCLUSIONS AND RECOMMENDATIONS

Nearly all of the objectives and goals for this project were successfully met or exceeded. Important accomplishments for the project included the following:

- This demonstration marked the first use in California of a dedicated natural gas truck with the high horsepower and torque needed to compete in Class 8 trucking applications. It was an essential step towards full commercialization of dedicated LNG tractors with upgraded, low-NOx DDC Series 60G engines. The funds provided by SCAQMD and DOE/NREL were essential to this achievement.

- Emissions certification testing on the upgraded Series 60G engine – as well as chassis dynamometer emissions testing of the LNG tractor at CaTTS – have further corroborated that heavy-duty LNG engines offer major NOx and PM emissions reductions compared to equivalent diesel engines.

- DDC's imminent certification of the upgraded S60G engine at 400 hp and 1450 lbs-ft of torque to California's optional low-NOx emissions standards is a major accomplishment. High commercial demand is anticipated for this engine, and a significant increase in deployment of heavy-duty LNG trucks may soon follow.

- It is conservatively estimated that the project resulted in between 1,000 and 1,800 pounds less NOx emissions in the South Coast Air Basin by deploying the LNG tractor instead of a comparable diesel tractor over the 47,000+ miles of demonstration.

- The use of project funds to support the Downtown LNG station served its short-term objective, by allowing the station to remain operational for approximately one year longer than it otherwise would have lasted. However, the longer-term goal – to keep the station open until self-sustaining demand for LNG fuel could develop -- was not realized.

Important "lessons learned" and recommendations derived from this project include the following:

- Much greater numbers of LNG vehicles on the road are needed to make LNG stations and technologies profitable for private industry. Low throughput remains a major barrier to expanding the LNG infrastructure, which in turn is the biggest barrier to wider deployment of LNG vehicles in Class 8 trucking applications.

- Running out of fuel (usually requiring towing) remains a significant problem for LNG trucks, due to the paucity of LNG stations and the following other factors: reduced vehicle range due to lower volumetric energy content of LNG; less accurate fuel gauges; the lack of extensive driver experience with LNG; the difficulty of getting cold fuel into relatively hot tanks with high vapor pressure; and the not-uncommon need to vent and service an LNG truck's onboard fuel system at a location remote from the nearest fueling station. Some of these issues require technical solutions (e.g., improved and larger on-board LNG storage tanks), while others involve institutional ones (e.g., improved training of end users).

- To move forward with LNG in trucking applications, it may be necessary for fleets to share LNG fueling facilities with transit districts that are aggressively moving forward with LNG buses, such as the Orange County Transit Authority.

- Additional work is needed to improve heavy-duty natural gas engine efficiency and fuel economy. Work of this nature is already underway or planned, through other government-funded programs.

2. INTRODUCTION

2.1 PROJECT BACKGROUND AND OBJECTIVES

Diesel-fueled heavy-duty trucks represent a small percentage of the vehicle population in California, but they contribute large percentages of the oxides of Nitrogen (NO_x) and on-road particulate matter (PM). Although the adverse air quality and health-effect implications of diesel exhaust are well known, the trucking industry relies on diesel-fueled heavy-duty engines because of their relative low cost and durable, reliable and efficient operation. For these reasons, the trucking industry has been reluctant to use alternative fuels and engines, which are associated with higher costs, a limited fueling infrastructure, and poorer durability and fuel efficiency. Despite these problems, the trucking industry is increasingly taking an active interest in alternative fuels and engines as a means to reduce levels of NOx and PM emissions.

One of the most promising alternative fuels for heavy-duty trucking applications is liquefied natural gas (LNG). Engines powered by LNG look especially attractive in Class 8 (>33,000-lb Gross Vehicle Weight) short-haul truck applications where large quantities of fuel are used, vehicles are centrally fueled, and routes contain multiple starts and stops. In the mid 1990s, government agencies such as the South Coast Air Quality Management District (SCAQMD), the Department of Energy (DOE), and the California Energy Commission joined with the major manufacturers of heavy-duty engines and vehicles to accelerate the pace towards developing, demonstrating, and commercializing LNG technologies for heavy-duty trucking applications.

In 1998, SCAQMD and DOE's affiliate, the National Renewable Energy Laboratory (DOE/NREL), joined to retain the services of ARCADIS Geraghty & Miller[3] and its subcontractors to improve the commercial viability of a promising LNG engine technology for Class 8 trucking applications. The project included the following key objectives:

- Upgrade a Detroit Diesel Corporation (DDC) Series 60 natural gas (S60G) engine in an existing LNG tractor for 400 HP and 1450 lbs.-ft. of torque.
- Operate the LNG tractor for approximately 12 months in revenue service hauling up to the full 80,000 lbs. GVWR, and document the performance compared to a tractor with a similar diesel engine.
- Cost share the upgrade of two additional Series 60G engines under a sister project primarily funded by the California Energy Commission, in which approximately 42 additional months of LNG tractor demonstration will be performed.

[3] On January 22, 2000, ARCADIS Geraghty & Miller's Transportation Technology Group became part of Arthur D. Little, Inc. (see box on page ii).

- Achieve California certification of the 330 horsepower DDC S60G engine for over-the-road LNG coach applications, and initiate efforts to certify the 400 HP version for trucking applications.
- Facilitate chassis dynamometer emissions testing on one LNG tractor (under outside funding as a project cost share).
- Extend the period of operation for the downtown Los Angeles LNG fueling station for approximately one year, through direct financial support.
- Document project results in Monthly Progress Reports and a Final Report.

2.2 PROJECT ORGANIZATION

ARCADIS Geraghty & Miller served as prime contractor for the project, and provided comprehensive technical and financial oversight. Figure 2-1 displays the organizational and contractual structure for the project .

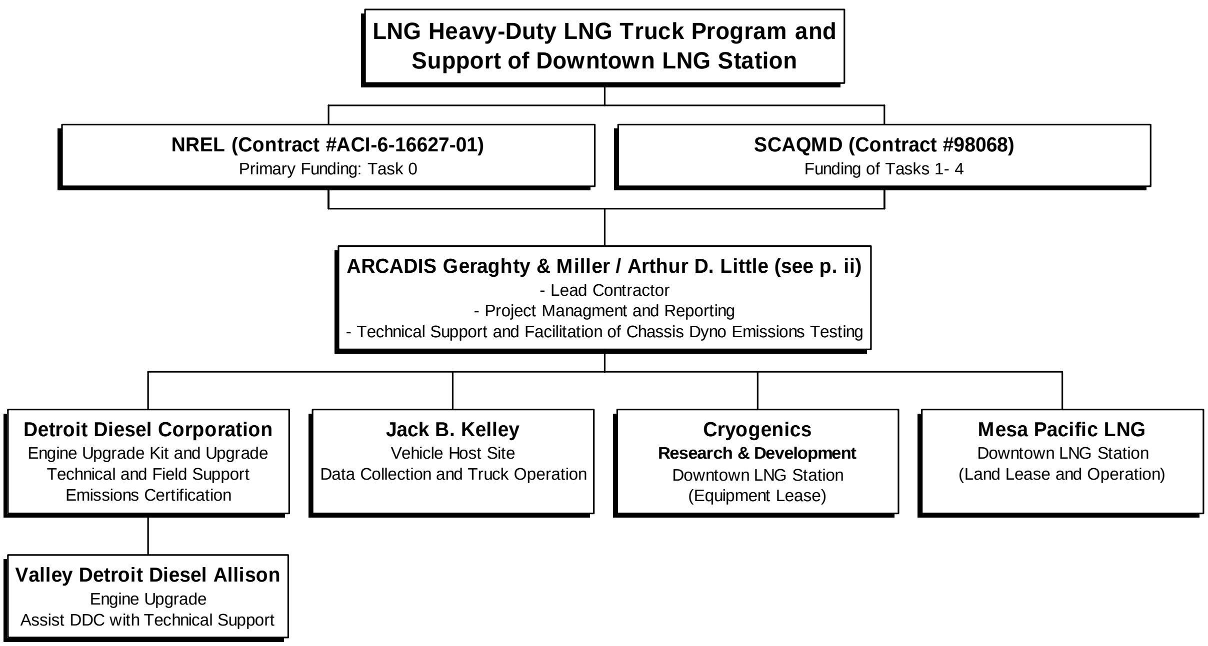

Figure 2-1. Project organizational structure.

2.3 PROJECT ORIGIN

The LNG tractor that was the primary focus of this project was one of five originally ordered by Ruan truck leasing, and leased by Liquid Carbonic, Inc. (LCI). These were the first tractors to be factory-equipped with an early version of the prototype LNG-fueled DDC Series 60G. LCI planned to dedicate the five trucks to hauling LNG from a new liquefaction plant in

Willis, Texas, to LNG customers in the Gulf Coast. The key customer for this planned business was Houston Metro Transit, which had made an early commitment to convert its transit bus fleet to LNG. Various technical problems with the LNG engines and fuel systems used by Houston Metro led the agency to delay, and ultimately, reverse its LNG conversion plan. As a result, only one of the five tractors was used significantly while leased to LCI.

In January 1996, LCI was sold to Praxair, which subsequently dissolved LCI's LNG business. The five LNG tractors were not operated while Praxair owned them, and they were offered for sale. Meanwhile, DDC had made significant improvements to the S60G engine and increased its performance to meet the demands of heavy-duty trucks, and was demonstrating a single Class 8 truck powered by this prototype version in Mobile, Alabama. Jack B. Kelley, Inc. (JBK) was interested in trying the same configuration in its Southern California fleet. JBK agreed to purchase three of the five tractors if government funding could be obtained and DDC could perform the same upgrade to the S60G engines for higher horsepower and torque. ARCADIS Geraghty & Miller developed the project further, and obtained funding from SCAQMD and DOE/NREL to upgrade and demonstrate one of the three LNG tractors. ARCADIS Geraghty & Miller also began the procedure to obtain additional funding from the California Energy Commission to upgrade and demonstrate the other two LNG tractors (described further under Subtask 1.6).

Another important part of the project involved providing financial support for the LNG station located adjacent to NGV Econtrans near downtown Los Angeles. This LNG station was not intended to be the primary refueling location for the JBK trucks, but it was expected to serve as an important cog in the limited LNG infrastructure for Southern California. The station consisted of LNG fueling equipment owned by JBK's affiliate, Cryogenics Research and Development. It was located on land owned and operated by Mesa Pacific LNG. The station had extremely low "throughput" (sales) of LNG fuel, because many of the LNG vehicles expected to be deployed in Southern California by the mid 1990s had not yet materialized. With the station being uneconomical to operate, the private sector interests were prepared to close it down in 1996. However, the station appeared to be a strategic interest towards future viability of the LNG infrastructure. Thus, a special task (Task 3) was developed under the SCAQMD-funded portion of the project, to keep the station open as long as possible, in the hopes that enough LNG vehicles would be deployed to make it self sustaining.

The SCAQMD / NREL project began in July 1998 after funding arrangements were finalized. ARCADIS Geraghty & Miller executed subcontracts with all parties noted in Figure 2-1 above. JBK arranged for the first LNG tractor to be towed from Texas to Valley Detroit Diesel Allison, in the City of Industry, California. This tractor was listed in the JBK fleet as #952268 (#68 for short). For simplicity in reporting project results, it was designated as "Tractor #1." As is described further in subsequent sections, "Tractor #2" and "Tractor #3" would subsequently be deployed with Tractor #1 in the JBK fleet, after the sister project funded by the California Energy Commission came on line several months later. Table 2-1 provides details about each of these three tractors and how the various funding dollars were allocated. Tractors #2 and #3 are shown in the table to demonstrate the relationship of the two projects (i.e., the project funded by SCAQMD/NREL and the sister project funded by CEC).

Table 2-1. Overview of funding sources for each of the three demonstration LNG tractors.

Demo Tractor	#1	#2	#3
JBK Fleet No.	952268	952269	952270
VIN Number	2FU5DZYB0SA424962	2FU5DZYB6SA424965	2FU5DZYBBSA424966
Odometer at Engine Upgrade ("As Received")	28,720	4,392	3,183
Date in Demo Service	02/09/99	11/2/99	11/2/99
SCAQMD Funding	Technical and field support, 12-month demo, differential costs for LNG tractor	Engine upgrade cost share	Engine upgrade cost share
DOE/NREL Funding	Engine upgrade and cost-share of DDC field support	None	None
CEC Funding	Extend demo by 6-months	Engine upgrade cost share and 18-month demo	Engine upgrade cost share and 18-month demo

NOTE: unshaded areas denote efforts funded under the SCAQMD and DOE/NREL cost sharing (i.e., work described in this report). Shaded areas denote efforts funded by the CEC under the ongoing sister project.

3. WORK PERFORMED AND RESULTS

As previously indicated, this project was cost shared by the SCAQMD and DOE/NREL. DOE/NREL funded Task 0 – Engine Upgrade, and SCAQMD funded all other tasks.

This section provides a description of the work performed under each task, and the results obtained. Where appropriate, tables, graphs, and photos accompany the text to display the results observed during the demonstration. A chronological overview of the demonstration can be found in

Table 3-2. Conclusions and recommendations are discussed in Section 5.

3.1 TASK 0 — ENGINE UPGRADE (FUNDED BY DOE/NREL)

The engine upgrade performed by DDC and VDDA under the project was designed to 1) improve the power, driveability and durability of the early-model S60G engine, to meet rigorous requirements of the heavy-duty trucking industry; and 2) further reduce emissions and fuel consumption. The specific hardware and modifications featured in DDC's upgrade kit included the following:

- **Advanced ignition system:** A new ignitions system with state-of-the-art coil-on-plug technology was installed to insure complete combustion with no external secondary spark plug wires.
- **Advanced fuel metering:** A re-mapped fuel system to refine fuel control. The regulator was re-configured to allow the use of a single unit in place of the original two regulators. The fuel control system was entirely engine mounted for more compact packaging and better fuel flow.
- **Improved combustion control:** The new system is closed-loop, incorporating an exhaust temperature sensor and an exhaust oxygen sensor. The exhaust 0_2 sensor provides constant feedback to the Electronic Control Module (ECM) to insure proper air/fuel ratios. The control system also has adaptive learning capability to update and refine the engine performance and driveability.
- **Other selected engine hardware:** Selected internal engine components were installed to improve durability and reduce oil consumption.

The first step in the project was for ARCADIS Geraghty & Miller to establish a subcontract with DDC to procure the necessary parts and perform the upgrade. In parallel, it was necessary to establish a subcontract with JBK, enabling it to purchase one of LCI's existing LNG tractors with the first-generation S60G engine. The JBK subcontract was quickly completed, and in late 1999 the first tractor was delivered to VDDA in Industry. However, it took significantly longer than anticipated to complete the DDC subcontract. This delayed the start of the engine upgrade until mid January 1999, when DDC delivered all the needed components for the upgrade to VDDA. Included in the upgrade package were cylinder kits, a new turbocharger, a fuel metering system, a fuel pressure regulator, an electronic controller, and a coil-on-plug ignition system.

Once under subcontract, DDC and VDDA quickly performed the engine upgrade using the upgrade kit and parts supplied by DDC. In tandem, ARCADIS Geraghty & Miller inspected the chassis and on-board LNG fuel system to identify needed upgrades. ARCADIS Geraghty & Miller worked with VDDA to determine that the tractor's LNG fuel system was in good, working condition. ARCADIS Geraghty & Miller then coordinated with VDDA and JBK to ensure that various other repairs and upgrades were performed, to ensure that the tractor was ready for on-road use. The entire process of upgrading the DDC S60G engine and tractor chassis was completed in late January 1999. Table 3-1 lists the final specifications for Tractor #1 after the engine upgrade.

Photo 3-1. LNG Tractor #1 at VDDA during the engine upgrade

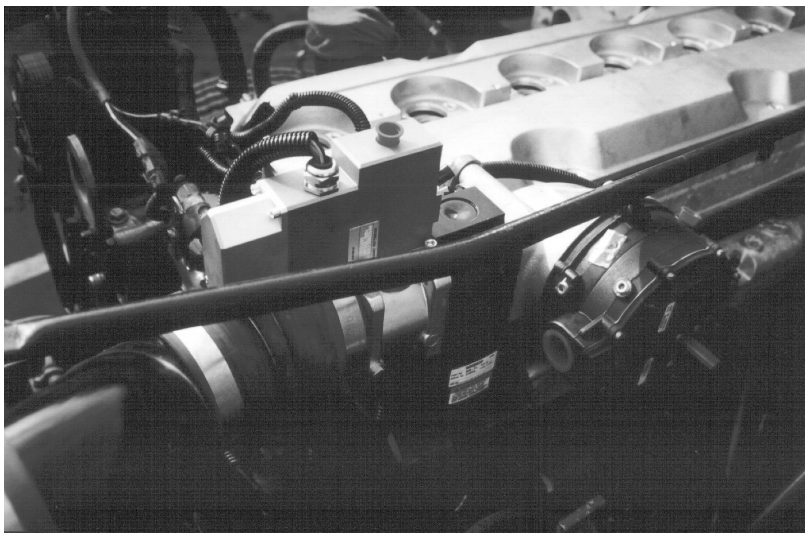

Photo 3-2. DDC S60G engine during the upgrade to 400 hp / 1450 lbs-ft.

Table 3-1. Tractor #1 system specifications

ENGINE	
Type	Detroit Diesel 400-hp Series 60G LNG
Compression Ratio	10:1
Rated Power	400 HP @ 2100 rpm
Peak Torque	1450 ft-lbs @ 1200 RPM
Displacement	12.7 Liters
Engine Control	DDEC IV, on-engine
Ignition	Electronically controlled, with coil on plug ignition
Engine Oil	40 quart capacity, special Mobil Delvac Super Geo oil for natural gas engines

CHASSIS & DRIVETRAIN	
Chassis Type	1994 Freightliner FLD 120
GVWR	80,000 lbs.
Cab	Conventional
Transmission	Rockwell, model #RM-10-145A
FUEL SYSTEM	
LNG Tanks	2 MVE LNG tanks, model #HLNG 119, net volume: 107 gallons; operating pressure: 120 psi Equipped with Parker nozzles Not equipped with vapor return fittings
Lines	Fill lines interconnect but a check valve prohibits filling both tanks from one side
LNG Vaporizer	Existing 1994-model MVE vaporizer for 300 HP HD engines was retained
EMISSION CONTROL SYSTEM	
Engine system	Lean calibration using speed-density airflow measurement, electronic fuel metering valve, engine control module and exhaust gas oxygen sensor; turbocharger with wastegate, recirculation valve, and air-to-air charge cooling; optimized ignition timing.
Sensors	Knock sensor, engine coolant temperature and level sensors, and exhaust gas temperature sensors are used by DDEC controller for engine protection purposes
DATA ACQUISITION EQUIPMENT & SENSORS	
Data Logger	Integral data logging features of DDEC IV ECM
Road Relay	DDC device that translates engine fault codes to English
Methane Detection System	AMEREX AMDGAS III methane detection system First sensor located over engine fuel metering system Second sensor located between the bulkheads of the twin LNG tanks (later relocated to the cab interior to be consistent with SAE J2343, and to prevent contamination by road debris).

The final requirement under Task 0 was to perform checkout testing, before delivering Tractor #1 to JBK. To assess the upgraded system's horsepower and torque, DDC and VDDA tested the tractor on VDDA's chassis dynamometer. During this testing, the tractor developed 368 hp at the rear wheels, which is equivalent to slightly more than 400 bhp at the flywheel. This test confirmed that the tractor would be able to meet the performance standards requested by JBK. ARCADIS Geraghty & Miller analyzed the raw data provided by VDDA and produced the graph in Figure 3-1 below.

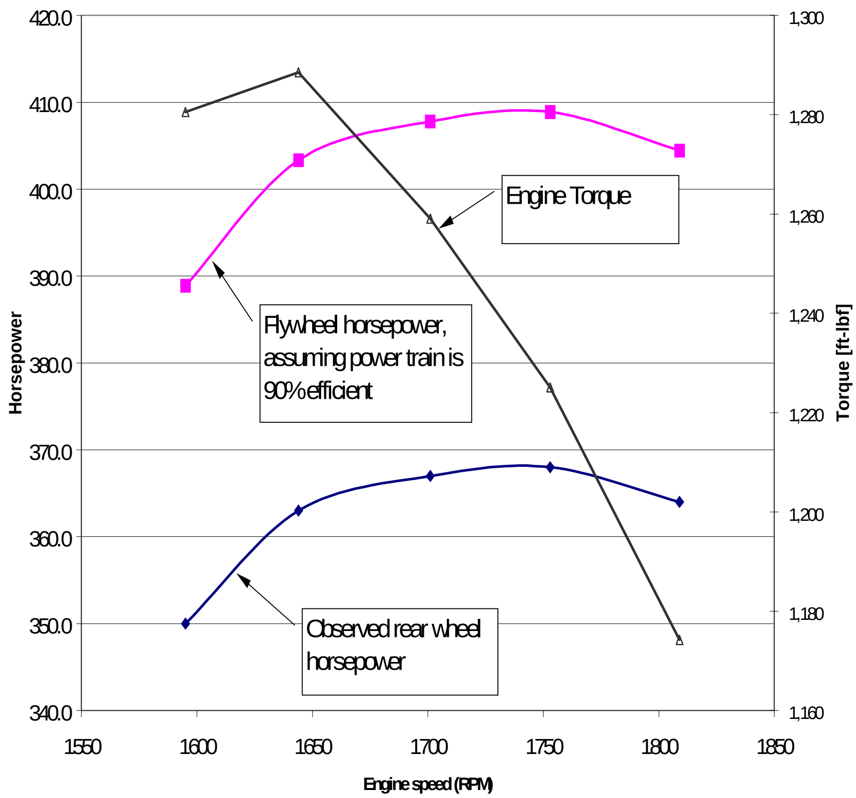

Figure 3-1. Performance testing results for Tractor #1 on VDDA's chassis dynamometer

3.2 TASK 1 — FIELD DEMONSTRATION

3.2.1 Overview of Task 1 Activities and Results

Once the engine upgrade was completed and checkout testing was performed, the demonstration was ready to begin. On January 22, 1999 the tractor was towed to the Ontario LNG fueling station for its first fueling of the demonstration. During the last week of January 1999, DDC completed efforts to fine tune the engine, and worked with JBK to prepare the tractor for commercial deployment. The following day, VDDA made component adjustments and the truck was test-driven by JBK staff for actual on-road checkout testing. ARCADIS Geraghty & Miller accompanied the JBK driver during this tesing.

During the test drive, the engine ran well and accelerated strongly, with almost none of the hesitation or misfiring that frequently occurred in earlier versions of the S60G engine. However, blue smoke and the odor of burning lubricating oil were also detected. This was thought to be due to poor performance of the oil-control rings prior to ring break-in and seating. ARCADIS Geraghty & Miller and JBK monitored this issue during the field demonstration by watching the level of oil consumption and worked with DDC to resolve the problem (see 3.2.5.3 Oil Consumption).

Following this inaugural on-road test run at the end of January, a preliminary load test was run in early February. However, when JBK's trailer was hooked up to the tractor, the power take-off (PTO) shaft and alternator on the truck were slightly damaged. JBK staff were able to resolve this problem, and the load test was conducted. Both DDC and JBK staff concluded that the LNG tractor provided sufficient horsepower and torque to perform in the intended service, i.e., Class 8 trucking at the full 80,000 lbs. GVWR.

LNG Tractor #1 began service as part of JBK's southern California fleet on February 9, 1999. Designated as the diesel control tractor was a JBK tractor (#961853) with the DDC Series 60 diesel engine. However, in June 1999 JBK decided to relocate this particular truck to Alabama. ARCADIS Geraghty & Miller worked with JBK staff to designate a new diesel S60 tractor as the control vehicle. Data collection for the second diesel control tractor began on July 13, 1999.

The LNG tractor ran extremely well throughout the initial nine months of demonstration, and was well received by its drivers. No emergency road calls were needed and the vehicle averaged approximately 5,000 miles per month. The only significant problem encountered was excessive oil consumption. At the quarterly project review meeting in mid 1999, DDC and the various project participants agreed to continue accumulating mileage on the tractor. The probable cause of the high oil consumption was identified to be rings that had been improperly installed in one or more cylinder.

In late 1999, after accumulating more than 47,000 miles of service, Tractor #1 was removed from service to troubleshoot the oil consumption issue and perform various engine and chassis upgrades. Ultimately, additional time was needed by DDC to perform calibration upgrades to the engine in parallel with its emissions certification efforts (see Task 2). Thus, Tractor #1 was out of service for approximately two months. When the demonstration ended in early February of 2000, the truck had accumulated about 48,000 miles and was operational approximately 80% of the time excluding the time needed to perform calibration upgrades. Details of the demonstration and the data collected are discussed below by subtask.

3.2.2 Subtask 1.1 – Field Support and Operating Permits

Under the structure of the project and its contracts, ARCADIS Geraghty & Miller was in charge of ensuring that comprehensive field support was provided for Tractor #1 during the 12-month demonstration. Assisting ARCADIS Geraghty & Miller under subcontract for this work were DDC and VDDA. Throughout the project, ARCADIS Geraghty & Miller, DDC and VDDA worked to ensure that all problems were resolved quickly. In addition, JBK staff expended significant resources to resolve problems that typically occur during demonstrations of prototype or commercially immature technology.

As previously noted, Tractor #1 operated with few major problems for most of the demonstration. The two events that required the most coordination were the actual engine upgrade and the repairs for the high oil consumption. A list of problems that were encountered during the demonstration and how they were resolved is provided in Section 3.2.5.

Part of ARCADIS Geraghty & Miller's efforts to provide comprehensive field support involved the need to obtain any necessary permits and certifications to operate Tractor #1 on the roads. Activities that ARCADIS Geraghty & Miller coordinated in this regard included the following:

- Contacted the California Highway Patrol to assess the latest requirements under Title 13 for operation of LNG-fueled trucks, and obtained a letter from the CHP and delivered to JBK.
- Applied for and received an experimental vehicle permit from ARB for the LNG truck, enabling it to be operated as an emissions prototype in California.
- Inspected the tractor for compliance with California Title 13, and contacted the fuel system manufacturer, Minnesota Valley Engineering (MVE), about the specifications to which the fuel system was designed.
- Purchased and installed a Parker LNG fill receptacle cover and MVE excess flow check valves.
- Fabricated and installed labels for various on-board LNG fuel systems, as required by Title 13 and/or SAE J2343.

3.2.3 Subtask 1.2 – Design Improvements

Working with ARCADIS Geraghty & Miller, DDC performed several design improvements on the S60G engine during the course of the project. After the hardware was updated for the engine upgrade, DDC downloaded new engine calibrations. DDC also accompanied the truck on a test drive and further adjusted the calibrations. Throughout the project, ARCADIS Geraghty & Miller remained in contact with DDC about any additional updates. The emissions certification testing in December 1999 produced additional engine data for calibration refinements (see Task 2 in Section 3.3). The engine control module (ECM) calibration used in the certified 400-hp Series 60G is referred to by DDC as the "Release 27" calibration. ARCADIS Geraghty & Miller coordinated with DDC to install the Release 27 ECM calibration in Tractor #1 (as well as #2 and #3 under the CEC sister project) when it became available in mid February. In addition to changes in lookup tables controlling air/fuel ratio and spark advance, an important feature of Release 27 is that it provides for fuel shut-off while the engine is being motored[4] This feature has potentially significant emission benefits, as it eliminates exhaust emissions during motoring.

The initial installation of Release 27 caused the engine's driveability to deteriorate. DDC therefore restored the earlier, uncertified, calibration, while diagnosing the cause of the driveability deterioration with Release 27. DDC traced the problem to a conflict between ECM instructions for maintaining the correct high idle speed when a power takeoff (PTO) accessory is used, and the new instructions for shutting off fuel flow during motoring. Since Tractors 1, 2 and 3 do not have PTO shafts, DDC resolved the problem by disabling the instruction set for PTO operation. As of the writing of this report, DDC and VDDA had recently reinstalled the new

[4] While motoring, the engine is being driven by the drivetrain. In this mode, it functions as a compressor that absorbs power from the flywheel.

calibration in Tractors 1, 2, and 3. Release 27 appears to work well with properly manufactured fuel metering valves and regulators, but has exhibited lean misfire and poor throttle response in some instances. The problems are usually solved by replacing the fuel pressure regulator once or twice. It appears that the pressure regulator exhibits some variability in flow behavior between one unit and the next , due to manufacturing tolerances. Compared to the previous ECM calibration, Release 27 incorporates leaner air/fuel ratios at both low- and full load. The previous calibration's excess air ratio (λ) was approximately 1.5 (equivalent to 25.8:1 on the basis of mass). Release 27 increased λ at these loads by approximately 0.03[5]. It also incorporates somewhat richer air/fuel ratios at high part-load cruise and during acceleration. This control strategy apparently makes the engine more sensitive to manufacturing variability in regulator performance. DDC and IMPCO (the regulator supplier) are currently working to solve the problem.

On several occasions during the project, ARCADIS Geraghty & Miller communicated with MVE (the fuel system manufacturer) to assess if any system upgrades were needed. During most of the demonstration, no changes were required. However, towards the project's end ARCADIS implemented several safety and labeling changes, to conform with evolving requirements from the CHP and to comply with Title 13. These changes are discussed in the previous section.

3.2.4 Subtask 1.3 – Methane Detectors

Subtask 1.3 required ARCADIS Geraghty & Miller to establish a regular inspection program for Tractor #1's on-board methane detectors to ensure proper operation at all times. Upon its delivery to VDDA and initial inspection, however, ARCADIS Geraghty & Miller discovered that Tractor #1 was not equipped with a methane detection system when it was purchased by JBK (unlike California, Texas does not require methane detection on LNG trucks). ARCADIS Geraghty & Miller researched options for the best course of action, and purchased a state-of-the-art AMEREX methane detection system. Among other features, this system is self-calibrating and does not require a special inspection program. This system was installed on Tractor #1 by VDDA in January 1999. The photo below shows the AMEREX methane detection system's display inside the cab of Tractor #1. Locations selected for the detectors were over the engine's fuel metering system, under the frame, and between the twin LNG tanks.

[5] Roger Parry, Program Manager, Alternate Fuel Project Center, Detroit Diesel Corpration, personal communication with Jon Leonard and Richard Remillard, 7 June 2000.

Photo 3-3. In-dash AMEREX methane detector display in cab of Tractor #1

False-positive readings on the AMEREX system were reported by the JBK driver in August 1999. After the fuel system was inspected and verified to be leak-free, ARCADIS Geraghty & Miller contacted the AMEREX dealer to discuss diagnostic and cleaning procedures for the methane detection system. It was concluded that the location of one detector had possibly contributed to the false positives due to contamination by road debris. However, no further false-positive readings occurred for several months. In November 1999, ARCADIS Geraghty & Miller determined that one of the detectors should be relocated to the cab of the truck, to comply with California Title 13 and SAE standard J2343. This would also reduce false-positive readings from road debris. JBK was informed of the need to move the detector location, and performed the work as a cost share to the project.

3.2.5 Subtask 1.4 – Data Collection

To meet the requirements of Subtask 1.4, ARCADIS Geraghty & Miller subcontracted with JBK to collect the following data parameters during the course of the demonstration for the LNG and diesel control tractors:

- Fuel consumption (with mileage and date)
- Oil consumption (with mileage and date)
- Routine maintenance (with mileage and date)
- Road calls (with mileage and date)
- Driver evaluations (as needed)

Upon collecting the data, each month JBK faxed it to ARCADIS Geraghty & Miller for compiling, analyzing and reporting in the monthly progress reports.

Regular data collection began in February 1999, when Tractor #1 entered revenue service with a starting odometer reading of 28,720 miles. Over the next 12 months, Tractor #1 accumulated 47,168 miles on the upgraded S60G engine.

Table 3-2 provides an overview of monthly mileage accumulations and problems encountered. Further descriptions are provided in the following sections.

3.2.5.1 Mileage Accumulation and Driving Route

Tractor #1 accumulated 47,168 miles with the upgraded LNG engine during its 12-month demonstration. This is approximately 80% of the mileage accumulated by a typical diesel tractor in JBK's fleet. The difference can be attributed to several factors, including the extensive downtime for servicing and upgrading the truck during the last two months of the demonstration (see

Table 3-2), and a lack of available drivers at JBK's Fontana depot. Additionally, the LNG tractor was largely used for local hauls (discussed more below) due to the difficult logistics of refueling with LNG outside Southern California. By contrast, JBK's diesel control tractor was routinely able to make line hauls to destinations such as Mexico and Arizona. Table 3-4 provides a comparison of the mileage and uptime for the LNG and diesel control tractors.

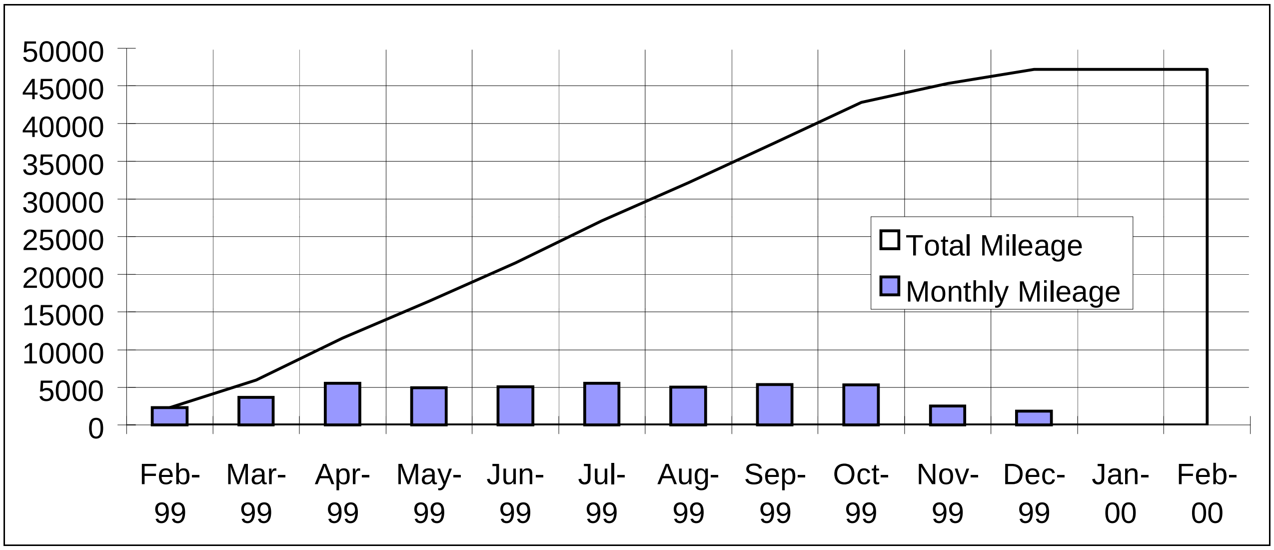

Figure 3-2. Monthly and cumulative mileage for Tractor #1.

Table 3-2. Summary of issues and solutions for Tractor #1 during 12-month demonstration

	Mileage: Monthly [Total]	EVENTS / PROBLEMS / RESOLUTION
Jan '99	0 [0]	Jan 27 test drive: Blue smoke and burning lube oil detected; thought to lack of break in for control rings.
Feb '99	2,319 [2,319]	Loaded trailer test drive: PTO shaft and alternator damaged when trailer hooked up; resolved by JBK. Tractor ran well in regular operation. Radiator fan occasionally hit its shroud; throttle controller released throttle too slowly when driver released throttle pedal.
Mar '99	3,658 [5,977]	March 23 Ride-along: DDC revised engine calibration, driver noted high oil consumption. Smooth and quiet engine idle. Driver noted that the S60G has better power and driveability than a CAT 3176B dual fuel engine. Some black smoke observed during hill climb. DDC noted engine somewhat rough, possible misfiring. March 24 VDDA Service: Spark plug electrodes clean and dry but gap 0.030" (spec: 0.015") -- likely cause of poor ignition under medium to high loads. DDC installed 6 new spark plugs. Combustion chambers clean and free of oil, but oil found in air compressor (shares lubricating system with engine). Likely cause: worn rings. Compressor rebuilt, water pump and coolant replaced. March 29: VDDA discovered engine coolant filter and corrosion inhibitor replacements incompatible with coolant, resulting in worn coolant pump. VDDA replaceed pump and coolant.
Apr '99	5,541 [11,518]	Socal Gas NGV Expo in Downey: Truck out of service for display 4/7 & 4/8. Regular Operation: Fault codes registered for low coolant level and high coolant temperature. VDDA found coolant level OK, ordered new sensor. JBK driver reported engine running well. Good power, but occasional engine fault and shutdown. April 28 VDDA Service: VDDA investigated engine fault, found code for faulty knock sensor; ordered replacement.
May '99	4,935 [16,453]	May 5 VDDA Service: VDDA replaces knock sensor, driveability improved. May 13 LA Freightliner BBQ: VDDA observed radiator fan not shutting off during low engine load. Slightly increased fuel consumption noted. JBK mechanic services tractor. Exhaust gas odor and appearance indicative of burning lube oil, confirmed by high oil consumption.
Jun '99	5,084 [21,537]	Regular Operation: No engine-related road calls and minimal engine service. Oil consumption high at approx. 1 qrt per 300 miles. Diagnosed as possible poor setting of rings or upside down installation due to changed marking procedure. June 20-22 San Ramon NGV Expo: Truck displayed at expo in Northern California.
July '99	5,549 [27,086]	Regular Operation: No engine-related road calls and minimal engine service. Oil consumption slightly improved, but still high. DDC plans to service the cylinder kit when second LNG truck is in service. DDC buys barrel of oil for JBK
Aug '99	5,058 [32,144]	Regular Operation: No engine-related road calls and minimal engine service. Oil consumption still high.
Sept '99	5,345 [37,489]	Regular Operation: No engine-related road calls and minimal engine service. False-positive readings from methane detectors, attributed to road debris. Excessive oil consumption continued. September 16 SCAQMD Workshop: Truck displayed at environmental journalist workshop.
Oct '99	5,310 [42,799]	Regular Operation: No engine-related road calls and minimal engine service. Excessive oil consumption continued.
Nov '99	2,532 [45,331]	Regular Operation: Out of operation from 11/1 through 11/15 because JBK had a shortage of drivers and to assign them to #2 and #3 for performance checkouts. November 22 – taken out of service for low fuel pressure on the engine gauge. Driver indicated that tractor was exhibiting diminished power and poor driveability. Symptoms indicative of clogging of the in-line fuel filter.
Dec '99	1,837 [47,168]	December 10 VDDA Service: Out of operation for remainder of month. Inspected for high oil consumption and investigated November problems. Filter plugged, cylinders 1, 3, and 6 fouled with oil. All 6 cylinder kits and filter replaced. Pressure relief valve replaced (old and of suspect performance).
Jan '00	0 [47,168]	VDDA Service continued from December: Cylinder kit installation completed. Methane sensor relocated to cab.
Feb '00	none before 2/9/00 [47,168]	VDDA Service continued from December: DDC downloaded the certified calibration (R27Chassis dyno testing not successful so change was reversed. (Problem subsequently resolved in extended demonstration under CEC funding, as discussd in §3.2.3.)

Table 3-3. Comparison of Monthly Mileage and Time in Service for LNG and Diesel Tractors

	LNG Truck #2	LNG Truck #2 Adjusted for Repairs*	Diesel Control**
Average Monthly Mileage	3900	4700	7400
Average Daily Mileage	250	250	330
% of Days in Service Compared to Diesel	70%	83%	100%

*This column shows the average mileage data excluding the two months that the truck was out of service for oil consumption repairs and recalibration.

**This refers to the second diesel tractor's service at JBK from 7/13/99 to 2/9/00.

As Figure 3-3 shows, there was high day-to-day variability in the number of miles that the LNG tractor was driven. ARCADIS Geraghty & Miller accompanied JBK on a ride-along on March 23, 1999 to document performance and the "typical" route (if one existed) for the LNG tractor. An average delivery of liquefied nitrogen (LN_2) took approximately two hours and included a combination of freeway driving, surface street driving, and extensive engine idling. Three to four round-trip deliveries were made each day, consisting of about 80 to 90 miles. Fully loaded, the combination weighed 80,000 lb. Having a cargo capacity of 7,500 lb, its payload of liquefied nitrogen is approximately 50,000 lb. This duty cycle served as a good test for the types of heavy-duty vehicle applications that are targeted commercial applications for the DDC Series 60G LNG engine, such as grocery store operations.

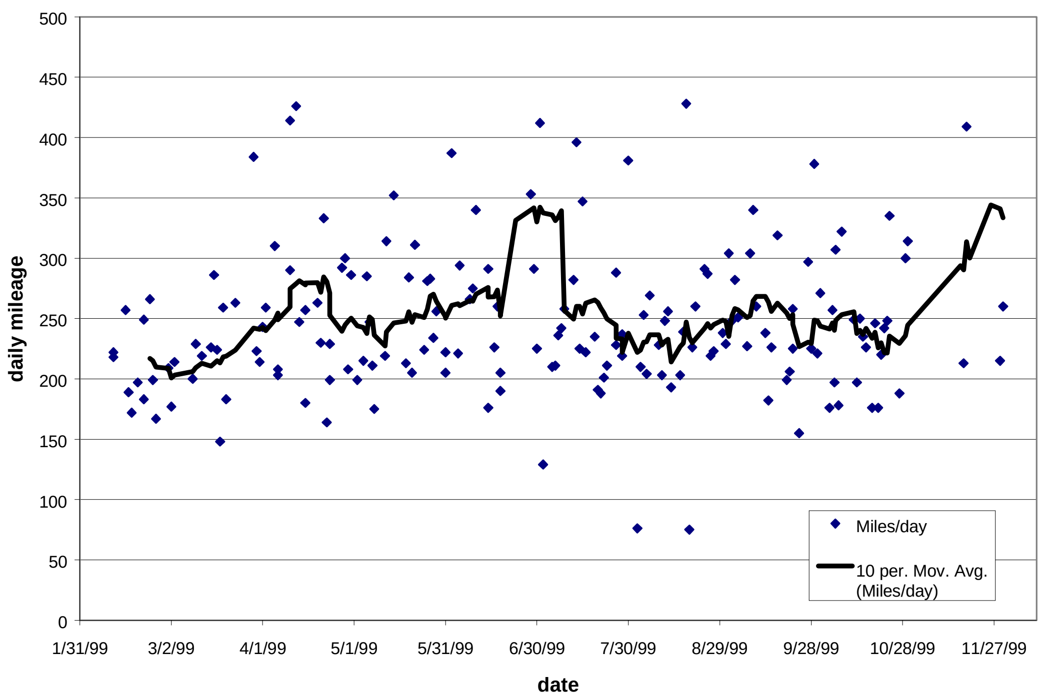

Figure 3-3. Daily mileage variation for the LNG tractor.

The drive-along test for the LNG tractor included climbing up a 5% grade (estimated) with a peak elevation of 3,500 feet (on SR 14 from I-5 exit to the high desert). Carrying somewhat more than a half load, the combination vehicle weighed approximately 60,000 lb during the climb. The tractor climbed the grade at 45 mph and met the driver's expectations for power.

3.2.5.2 Fuel Consumption and Efficiency

The average monthly fuel economy for Tractor #1 through December 1999 ranged between 2.8 to 2.9 miles per gallon of LNG. This is equivalent to approximately 4.8 miles per diesel-equivalent gallon (mi/DEG). The diesel control tractor (with a Series 60 diesel engine) averaged 5.9 mpg. The average fuel economy for JBK's fleet of diesel tractors – most of which use the Cummins M11 diesel engine – was 6.0 mpg.

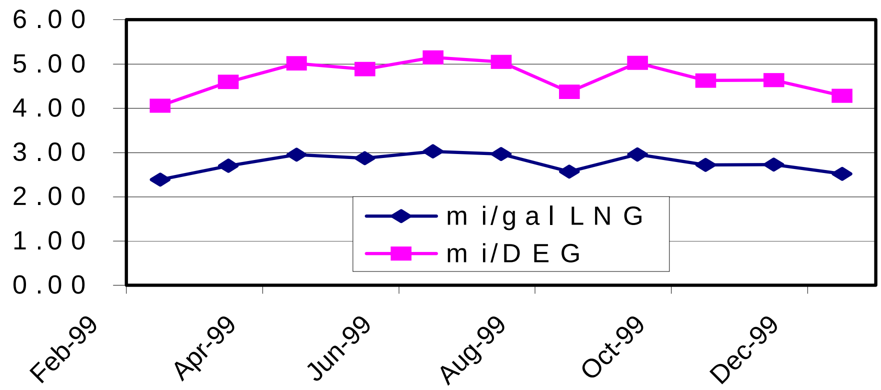

Figure 3-4. Average monthly fuel economy for Tractor #1.

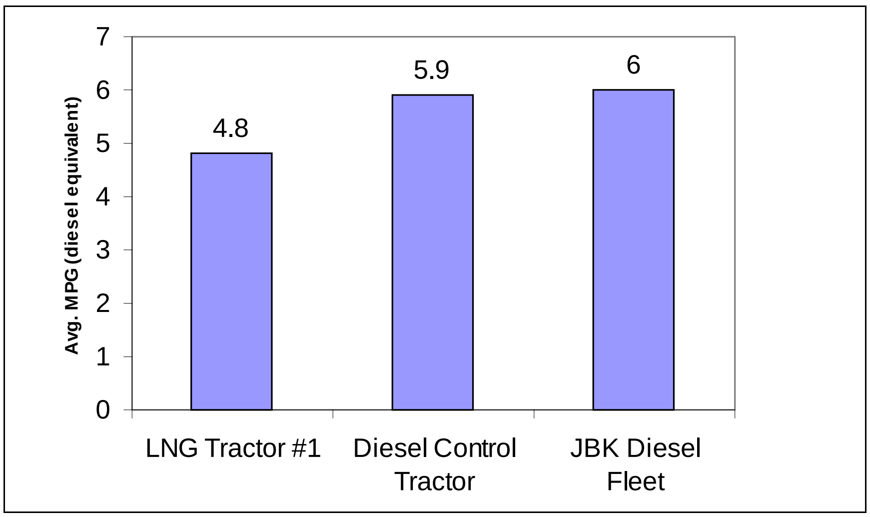

Figure 3-5. Comparison of fuel economy for LNG and diesel tractors.

These data indicate that on average, the LNG tractor achieved approximately 81% of the fuel efficiency of the diesel control tractor. In addition to the normal efficiency loss that occurs when a compression-ignition engine is converted to spark ignition, the following other factors probably contributed to the lower fuel efficiency for the LNG tractor:

- Excess LNG venting during refueling probably occurred periodically throughout the demonstration. Causes for this may have included 1) a lack of complete familiarity with LNG fueling procedures by JBK's drivers) and 2) non-optimized performance of various pressure relief valves and other on-board LNG fuel system components, some of which were replaced towards the end of the demonstration.
- A high degree of day-to-day variation in the tractor's service route and duty cycle.
- Inaccuracy of fuel fills at the Ontario station, which will be receiving a technology upgrade in the future under GRI and SCAQMD funding.

3.2.5.3 Oil Consumption

Under Subtask 1.4, ARCADIS Geraghty & Miller worked with JBK to track the use of engine oil for the LNG truck and obtain oil sample reports. JBK’s service schedule for diesel and LNG tractors calls for changing the lubricating oil at intervals of 15,000 miles, or 2 to 3 months. Oil samples were taken during oil changes and sent to Castrol labs for analysis. JBK forwarded the reports to ARCADIS Geraghty & Miller if any unusual results were found. Oil analyses for Tractor #1 indicated no problems during the demonstration. However, in mid-December 1999, an oil analysis performed during scheduled servicing of Tractor #3 revealed likely lube oil contamination by engine coolant. This oil analysis (Figure 3-6) enabled VDDA to investigate the problem and repair a failed oil seal in the water pump.

Oil Analysis Report
Laboratory: Pennzoil
JBK Fleet No.: 952270
Sample Date 12/15/99

Spectrochemical Analysis [parts per million]

Element	Iron	Chromium	Lead	Copper	Tin	Aluminum	Nickel	Silver	Silicon	Boron	Sodium	Magnesium	Calcium	Barium	Phosphorus	Zinc	Molybdenum	Titanium	Vanadium	Potassium	Fuel
Concentration	41	4	19	4	0	4	0	0	9	134	139	0	3104	0	1001	1690	2	0	0	999	<.5
Abnormal											**A**										
Critical																				**C**	

Physical Properties

	Viscosity [cSt @ 100C]	Water [%]	Soot /Solids	Glycol
Result	14.52	<.1	0.9	POS
Abnormal				
Critical				**C**

Analysis recommendations:

Severe level of coolant (glycol) detected. Inspect for source of internal leak. Change oil and filter if not done at time of sampling. Resample at one-half normal interval. Results reported by phone / fax.

Figure 3-6. Oil sample analysis used to troubleshoot engine problems on Tractor #3.

Oil consumption was monitored in between oil changes, by recording the date and odometer reading on which make-up oil was added, and the volume of oil added. Early in the demonstration, records indicated that oil consumption for Tractor #1 was high. Initially, it was assumed that the high consumption rate was related to engine break-in behavior, but after the problem continued for approximately 5,000 operating miles, this was eliminated as the problem. Oil consumption remained high for the remainder of the demonstration. In addition, high variability occurred in the amounts of makeup engine oil that were added by JBK staff, from month to month. However, it's possible that this reflects inaccurate record keeping.

Inspection of the engine indicated that the air compressor was part of the high oil consumption problem. Since it shares a common lubricating oil supply with the engine, high lube-oil consumption rates can result if the air compressor has worn or damaged rings. Replacement of the compressor with a remanufactured unit resulted in a small improvement in the engine's oil consumption. As Figure 3-7 shows, the average oil consumption rate for JBK's diesel fleet is 1,500 miles per quart, while data for LNG Tractor #1 showed rates averaging only about 400 miles per quart. As a near-term solution to offset JBK's high cost of oil for the tractor, DDC purchased a barrel of oil for the tractor. In the meantime, all project participants agreed that Tractor #1 should continue to accumulate mileage in the JBK fleet until the second and third LNG tractors could be deployed, under the CEC-funded "sister" project.

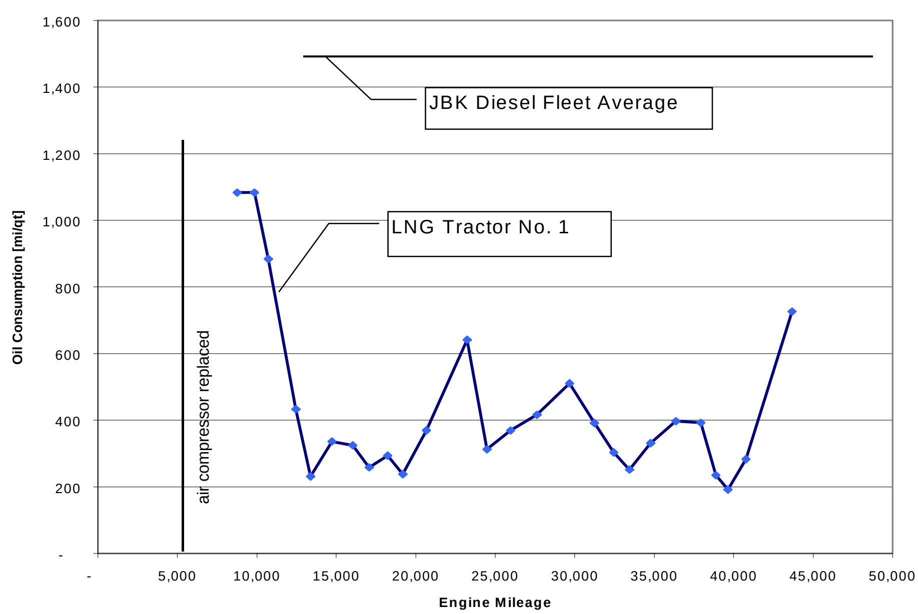

Figure 3-7. Oil consumption rates recorded for LNG Tractor No. 1.

During further diagnostics of Tractor #1's engine at VDDA in November 1999, cylinder No. 6 showed fairly heavy oil fouling on the spark plug. VDDA and DDC personnel agreed that the ring pack in this cylinder was probably either improperly installed, or defective. Servicing for the ring problem occurred in December 1999, and extended through the completion of the demonstration. Removing the head revealed that three cylinders were oil-fouled, with the fouling in No. 6 being much worse than the other two cylinders. To insure that all 6 cylinders would be put in proper condition, DDC authorized replacement of rings and cylinder liners in all six kits. However, VDDA did not have six kits in stock, and the holiday shutdown caused a delay in receiving them from DDC.

DDC carefully inspected the parts removed from the engine during servicing of the cylinder kits. The oil control ring on cylinder No. 6 was found to be kinked. This was likely the result of a manufacturing defect, and would account for the high oil consumption rates for Tractor #1 that were observed during its 47,000 miles of demonstration. At the time this report was written, Tractor #1 was back on the road for JBK, with a much lower oil consumption rate. However, more mileage must be accumulated (under the CEC-funded extension) before this can be confirmed.

3.2.5.4 Routine Maintenance

Routine maintenance was periodically conducted by JBK personnel during the 12-month demonstration, and was documented through standard forms. In August 1999, since it was better equipped to service LNG systems, VDDA offered to perform routine maintenance on the LNG tractor for the same price as JBK would incur doing it in-house. This offer was declined because of the logistical difficulty of transporting the truck and drivers between the two locations. (See previous sections for data gathered during routine maintenance at JBK.)

3.2.5.5 Road Calls

No emergency road calls occurred during the 47,000+ mile demonstration of Tractor #1. There were, however, problems noted while driving that were taken care of in subsequent service calls.

Table 3-2 above lists the relatively minor problems that were encountered and the steps taken to fix them. Aside from the downtime associated with fixing the oil consumption problem (discussed in Section 3.2.5.3), the only incidents that impeded operation were a faulty sensor that caused occasional engine faults and shutdowns in April 1990, and a clogged fuel filter in November 1999.

3.2.5.6 Driveability and Performance

One key factor in assessing the commercial viability for LNG-fueled heavy-duty trucks is how drivers perceive their performance compared to the diesel vehicle they normally operate. Driver input is also important because drivers are usually the first to detect a problem in the system. The general practice by JBK at its Fontana depot is to assign multiple drivers to its various diesel-fueled tractors. For the LNG tractor demonstration, a different system was set up. In the interest of minimizing variability and maximizing safety and data collection effectiveness, JBK assigned a select few drivers to operate the LNG tractor and the diesel control tractors. For example, the primary driver throughout the 12-month demonstration was chosen in part because he had previous experience operating a tractor equipped with the Caterpillar / Power Systems dual-fuel engine. This system of using the best-fit drivers was followed as much as possible without negatively impacting JBK's normal operations and driver rotation system.

During the course of the demonstration for LNG Tractor #1, ARCADIS Geraghty & Miller collected frequent input from the drivers through site visits, phone calls and inspection of the driver's log kept in the truck. The general comments from the drivers indicated that they were happy with the LNG tractor's performance, especially in comparison to the dual fuel technology. However, most did not like the extra time that it took to fuel the LNG tractor compared to a typical diesel tractor (discussed further under Task 3 – LNG Fueling).

Table 3-2 summarizes feedback from JBK drivers on the LNG tractor.

ARCADIS Geraghty & Miller also received feedback from the California Truck Testing Services (CaTTS) laboratory about driveability of one LNG tractor during chassis dynamometer emissions testing (see page 3-26 for details about emissions). The CaTTS technician drove the LNG tractor extensively on the dynamometer, following three different driving cycles (Modified CBD, Commuter, and UDDS) . He noted that the engine had good power and torque compared to a similar diesel engine, but he found the driveability to be hindered somewhat by a transmission poorly matched with the DDC Series 60G engine. Figure 3-8 shows the speed versus time trace of the Modified Central Business District cycle (CBD), compared to the dynamometer roll speed of the LNG tractor during testing (dotted line). This graph shows that the LNG truck was able to provide the hard accelerations required by the test cycle, but it is also indicative of the shifting problem noted by the driver. Table 3-4 provides a summary of the driver's observations about the shifting problem.

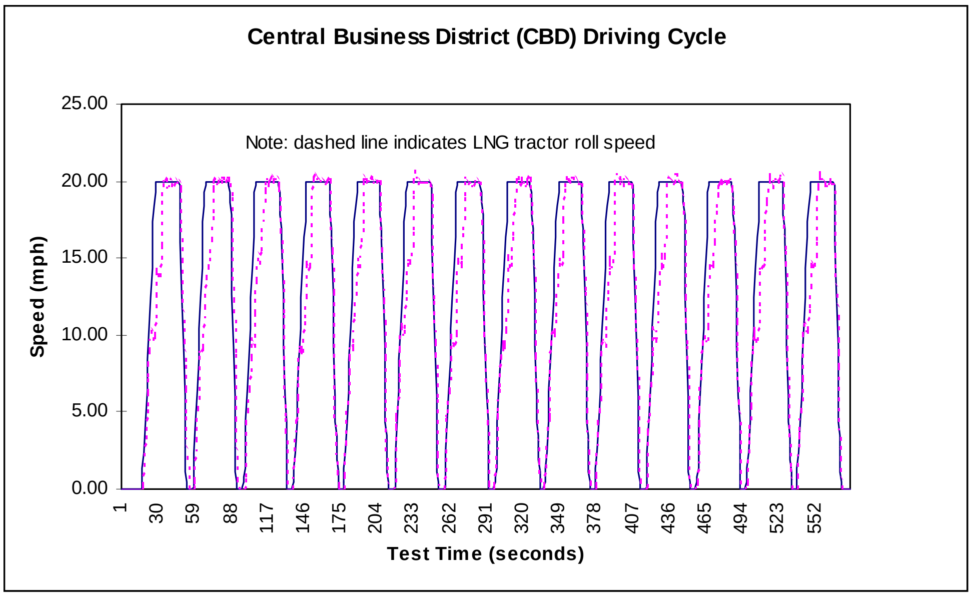

Figure 3-8. Acceleration of LNG Tractor during CBD cycle at CaTTS

Table 3-4. Comments of CaTTS driver on LNG tractor driveability.

1.	Accelerator lag doesn't allow the engine to slow to the speed necessary to synchronize with the next higher gear.
2.	Rockwell 10-speed manual transmission is geared low in the first 3 gear positions with large "gaps" between 3-4 and 4-5.
3.	The above two conditions made it difficult to follow a driving trace, because momentum is lost waiting for the engine speed to slow to the next synchronized point. The first condition affected CBD cycle testing, while the second affected the Commuter and UDDS cycles.
4.	Similarly, the reverse of this situation precludes downshifting, which places additional strain on the brakes.

It is important to stress that the technological advancement for this project involved the upgraded Series 60G engine and not the tractor itself. Future commercialization of the engine will be in tandem with an optimized chassis, transmission and on-board fuel system.

3.2.5.7 On-Board LNG Fuel System

When Tractor #1 was purchased by JBK from LCI and delivered to VDDA for the engine upgrade in early 1999, it was equipped with an on-board LNG system from MVE that was already several years old. For this reason and because the tractor had not been used significantly for several years, ARCADIS Geraghty & Miller and its subcontractors performed a checkout of the MVE system when the tractor was delivered to VDDA. Based on this inspection of Tractor #1's LNG system at VDDA and information provided by DDC regarding the earlier upgrade of a sister truck, it was concluded that no major work was needed to return the system to operation.

This LNG system performed well throughout the demonstration, although it was not state of the art. For example, the MVE system had not been originally designed for single point refueling of both LNG tanks (i.e., there was no functional crossover link between the two tanks). This required the JBK drivers to turn the truck around to facilitate refueling of both tanks, because the refueling connections at the Ontario LNG station were not long enough otherwise. Since the Ontario station is slated for a major upgrade under GRI and SCAQMD funding, it was not cost-effective to install longer fueling connections.

During the demonstration, several minor upgrades of Tractor #1's LNG fuel system were performed by ARCADIS Geraghty & Miller and its subcontractors. First, a clogged in-line fuel filter was replaced in November 1999. In December 1999, the pressure relief valve was replaced because it was old, and its counterpart on Tractor #2 had caused faulty venting. Finally, to comply with California Title 13, ARCADIS Geraghty & Miller ordered and installed MVE excess flow check valves and a Parker LNG fill receptacle cover.

One problem that came to light during the demonstration was the logistical difficulty of servicing the fuel system of the LNG tractor at a location that was not equipped for onsite LNG fueling. When ARCADIS Geraghty & Miller and VDDA removed and replaced fuel system hardware in late 1999 to upgrade the LNG tractor, all onboard LNG fuel had to be vented first. In addition to the loss of valuable fuel, this required towing the tractor to the Ontario station (approximately 25 miles one way) when the work was completed. Similarly, when the LNG tractor was parked for extended periods at VDDA awaiting parts and service, it lost enough fuel through boil off to require towing to the Ontario station. This fuel-system-related limitation -- coupled with the problem of a very limited LNG station infrastructure – highlights a significant current barrier for wider deployment of LNG-fueled vehicles. Mobile fueling of LNG trucks is a potential interim solution, but it is not widely practiced or economical due to the current paucity of LNG vehicles.

3.2.6 Subtask 1.5 – LNG Training

Shortly after the engine upgrade was completed on Tractor #1 and it was delivered to JBK, ARCADIS Geraghty & Miller joined with DDC to implement a training session at JBK's Fontana depot. Topics covered included LNG properties, safety, fueling procedures, and environmental benefits. Attending for JBK were drivers, maintenance personnel, and depot managers.

3.2.7 Subtask 1.6 – Engine Upgrades for Tractors #2 and #3

In mid 1999, ARCADIS Geraghty & Miller's contract with SCAQMD was amended to add Subtask 1.6 to Task 1. This called for SCAQMD to cost share the engine upgrades for two additional LNG tractors, as part of the CEC-funded sister project. Specifically, $13,379 in SCAQMD funds were set aside for this purpose, with CEC paying for the remaining portion of the two engine upgrades.[6] The elements of this arrangement and how each LNG tractor was funded are listed in Table 2-1 (see page 2-4).

In August 31, 1999 a new contract was executed with DDC to perform the engine upgrades on Tractors #2 and #3, under CEC funding with SCAQMD cost sharing. The engine upgrades were completed on October 1, 1999. The following two photographs show Tractors #2 and #3 just after DDC completed the engine upgrades. While the SCAQMD cost share for this process was relatively small compared to CEC's funding, LNG tractors #2 and #3 could not have been deployed without it.

Photo 3-4. Tractor #2 is towed to the Ontario LNG station for initial fueling after its engine upgrade (cost shared by SCAQMD).

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[6] The SCAQMD governing board originally approved the project funding in an amount that was $13,399 higher than the contract that was executed before the amendment, so these funds were applied to Task 1.6. The CEC sister project could not have proceeded without this cost share from SCAQMD.

Photo 3-5. Tractor #3 undergoes performance testing on the VDDA dynamometer.

To date, LNG tractors #2 and #3 have accumulated thousands of miles under the CEC sister demonstration. In addition, Tractor #3 was selected for the chassis dynamometer emissions testing that was conducted at the laboratory of California Truck Testing Services (CaTTS) in Richmond, California (described further under Task 2 in Section 3.3). Tractors #2 and #3 will be in demonstration service at JBK until mid 2001. Detailed reporting on their progress can be found in the quarterly reports for the CEC project (CEC contract #MHD-98001), which will be copied to SCAQMD and DOE/NREL (as will the final report).

3.2.8 Special Events and Workshops

In addition to the regular service in the JBK fleet described above, Tractor #1 was also exhibited at several alternative fuel vehicle workshops. These special events served to educate decision makers and the general public about opportunities for clean transportation. ARCADIS Geraghty & Miller arranged for the vehicle to be delivered to the workshops, prepared literature on the project for displays, and attended the workshops to answer questions. Driver delivery costs for the events were paid by project funding or provided as a cost share by JBK. Table 3-5 provides a summary of the events where Tractor #1 was displayed.

Table 3-5. Special Events and workshops where Tractor #1 was displayed.

Event or Workshop and Location	Date(s)	Purpose / Target Audience
SoCal Gas Natural Gas Vehicle Expo, Downey, CA	April 7 – 8, 1999	Display truck to prospective fleet users and chassis OEMs, including Freightliner, Ryder, ACE Hardware, and Harris Ranch
Freightliner's AFV BBQ Luncheon, Whittier CA	May 13, 1999	Display truck to potential fleet users (Freightliner considering commercial potential).
Pacific Gas & Electric Natural Gas Vehicle Expo, San Ramon, CA	June 23, 1999	Display truck to Northern California fleet users.
SCAQMD Environmental Reporter Conference, Diamond Bar, CA	September 16, 1999	Display truck to environmental reporters for SCAQMD.

3.3 TASK 2 — EMISSIONS TESTING

One of the key objectives of the project was to facilitate the commercial introduction of the upgraded, high performance DDC Series 60 natural gas engine by 1) achieving emissions certification in California, and 2) obtaining chassis dynamometer emissions data to corroborate its low-emissions potential in real-world use. Both objectives were achieved, as described below. As a result, the S60G engine has been moved closer to sustainable commercialization, especially since it now qualifies for clean-vehicle incentives such as funding offered through the Carl Moyer Program.

3.3.1 Certification Testing

The 400 horsepower version of the DDC Series 60G natural gas engine successfully completed emissions testing at Southwest Research Institute in December 1999. DDC submitted the results to both EPA and ARB in late January 2000, with a request for certification via a running change from the previously certified 330 hp version. Table 3-6 shows the results of the certification testing with an emission data engine at SwRI.

Table 3-6. Certification test results at SwRI for the 400 HP DDC S60G natural gas engine.

Exhaust Emissions Test	MAX TORQUE (lb-ft)	RATING (hp @ rpm)	BSNOx (g/bhp-h)	BSNMHC (g/bhp-h)	BSCO (g/bhp-h)	BSPM (g/bhp-h)
Federal Test Procedure	1450	400@2100	1.95	0.51	1.79	0.010

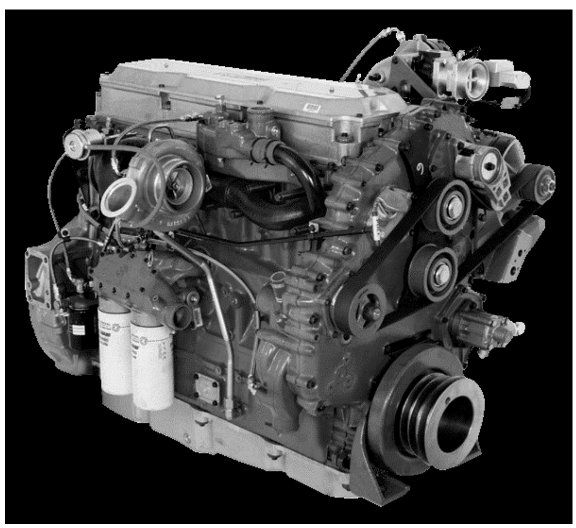

Photo 3-6. Detroit Diesel Series 60G engine. Photo courtesy of DDC.

A summary of the activities by DDC and ARCADIS Geraghty & Miller during this process to certify the 400 horsepower LNG-fueled Series 60G engine in California is provided in Table 3-7.

Table 3-7. Chronology of emissions certification process for the 400-hp DDC S60G LNG engine

Month	Event / Work Performed
Sep '98	DDC completes 49-State certification of the 330-hp version of the upgraded S60G engine for CNG applications only. The results (without an oxidation catalyst) indicate upgraded engine will meet California's optional low-NOx standard.
Oct '98	ARCADIS Geraghty & Miller works with DDC to preliminarily assess the potential to certify the LNG version of the upgraded S60G engine.
Jan '99	DDC reports that its application for California certification is under evaluation by ARB. DDC also confirmed that the engine was certified to the conventional 4.0g/bhp hr NOx standard, and not to an optional low-emission standard. DDC assesses the market demand for a 400 hp version of the S60G for the trucking market. DDC decides that a low-NOx certification of the engine would result in significant demand through its eligibility for Carl Moyer program funding and other incentives.
Feb '99	ARCADIS Geraghty & Miller reviews DDC's preliminary certification for the urban bus engine. ARCADIS follows up with DDC about certifying the 400-hp LNG truck engine.
April '99	ARCADIS assembles additional information for DDC about benefits of certification to optional low-NOx standard, including financial incentives for users.
July '99	DDC reports that it will apply for certification for the 330-hp LNG S60G in tandem with the 275-hp LNG S50G. DDC schedules certification emissions testing at SWRI.
Aug '99	ARCADIS Geraghty & Miller investigates status of DDC progress through discussions with relevant parties and prepares a detailed written update (see Appendix).
Sept '99	ARCADIS Geraghty & Miller contacts DDC to confirm that plans are on track to emissions test the 400-hp engine at SWRI in early October.
Nov '99	DDC confirms that the 400-hp S60G LNG engine had been installed in a test cell at SWRI with testing scheduled to begin in December.
Dec '99	DDC reports that the S60G LNG engine completed testing at SWRI.
Jan '00	Certification reports submitted to EPA and CARB with running change request.
Feb '00	DDC downloads the ECM calibration from the SWRI test (R-27) to the three JBK trucks (see photo), with field assistance from ARCADIS Geraghty & Miller. Driveability problems are documented and addressed. New PSVs, regulators, and oxygen sensors are ordered.
Mar '00	DDC and VDDA install the new PSVs and regulators and adjust all three trucks to the new calibration. Leaner setting found to make the systems especially sensitive to the operation of the fuel regulators. Tractor #1 is tested on the VDDA chassis dynamometer and performance is documented.
Mar '00	Approval from ARB is imminent for running change request; certification of LNG-fueled 400 HP Series 60G engine is essentially complete.

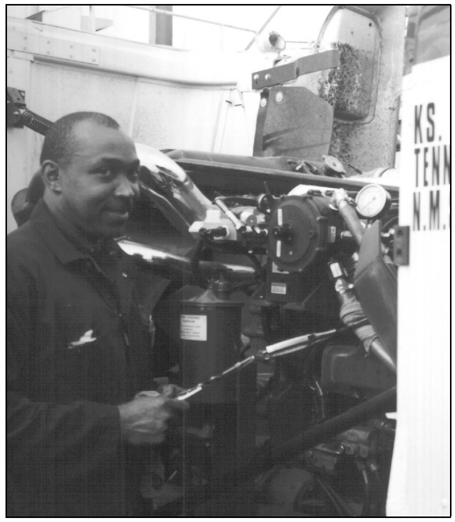

Photo 3-7. VDDA technician changes the LNG tractor's regulator after DDC installed the R27 calibration (photo by ARCADIS Geraghty & Miller).

DDC's R27 ECM calibration has a leaner fuel setting than the original calibration. As the photo above indicates, after the new R27 calibration was installed it was necessary to install a more compatible LNG regulator on the tractor. In early 2000, DDC and VDDA collaborated to fix the regulator problems on each of the three LNG tractors and adjust the fuel tables and rpm cutoffs. ARCADIS Geraghty & Miller staff spent extensive time at the site during these repairs, to document the work and take photographs.

Photo 3-8. Roger Parry (DDC), inspecting the final changes after downloading the R27 calibration (photo by ARCADIS Geraghty & Miller).

3.3.2 Chassis Dynamometer Emissions Testing

Another important part of Task 2 called for ARCADIS Geraghty & Miller to help facilitate chassis dynamometer emissions testing of a JBK tractor with the upgraded DDC S60G engine. While the actual emissions testing was beyond the project's budget, a key goal was to seek and procure testing under another source of funding, as a cost share for the SCAQMD and DOE/NREL funding. One option was to conduct the testing at the laboratory of the Los Angeles County Metropolitan Transit Authority (LACMTA), under an obligation that LACMTA holds to SCAQMD for testing from a previous contract. However, the LACMTA lab was closed for testing during the duration of the project. Thus, as the project progressed, ARCADIS Geraghty & Miller investigated other no-charge options for chassis emissions testing at other facilities.

In late 1999, ARCADIS Geraghty & Miller had discussions with Pacific Gas & Electric (PG&E), which was interested in emissions testing a tractor with the upgraded DDC S60G engine at the California Truck Testing Services (CaTTS) laboratory. This was part of PG&E's program to assess the effect on NOx emissions of various non-methane components commonly found in CNG fuel (e.g., ethane, propane). ARCADIS Geraghty & Miller agreed to discuss the issue with DDC and seek permission to conduct the testing. However, a potential problem was that none of the three LNG tractors in the JBK fleet had accumulated sufficient mileage after engine work to achieve proper break in. This raised concern that the particulate and hydrocarbon emissions might not be representative of a properly broken-in engine. DDC and ARCADIS Geraghty & Miller discussed the issue with PG&E, and it was noted that the test methodology was focused on NOx emissions as a function of fuel quality. PG&E intended to report data only by generic engine information (e.g., "Engine A"). Thus, it was agreed by DDC and ARCADIS Geraghty & Miller that this free chassis dyno testing at CaTTS offered no down side, and should proceed as soon as sufficient engine break-in was achieved on one of the three JBK trucks.

In March 2000, final arrangements were made between CaTTS, ARCADIS Geraghty & Miller and JBK to deliver one of the LNG tractors to the CaTTS laboratory. Tractor #3 (JBK fleet #70) was chosen for the testing because it was available at the time, and operating well. A CaTTS staff member flew down from Oakland to Ontario Airport, where ARCADIS Geraghty & Miller staff picked him up. Next, they met the JBK driver with Tractor #3 at the Ontario LNG station, where it was fueled. That same day, the CaTTS staff member drove Tractor #3 to the CaTTS laboratory in Richmond (near Oakland), refueling along the way at Harris Ranch.

While at the CaTTS laboratory, Tractor #3 was emissions tested on both LNG and CNG fuel, using multiple test cycles. For LNG testing, the test matrix included four different driving cycles on the tractor with its "as-received" fuel. Driving profiles ranged from the Central Business District (CBD) cycle with hard accelerations, to the Commuter cycle consisting primarily of a single, four-minute cruise at 50 mph. Other tests that were conducted included the Modified Central Business Cycle (MCBD) and the Urban Dynamometer Driving Schedule.

Results from the CaTTS testing of Tractor #3 were very preliminary at the time this report was finalized. Emission levels from the tractor exhibited high variability over the various test cycles, in part due to the lack of engine break-in miles. NOx levels ranged from as low as 2.7 grams per mile on one MCBD cycle to 8.6 grams per mile on one CBD cycle. Particulate matter emissions were not finalized but were higher than might be expected from a natural gas engine. This is also probably attributable to lack of break-in miles.

Obtaining an "apples-to-apples" comparison of emissions from the S60G-powered LNG tractor to a conventional tractor with the S60 diesel engine was not possible at the time this report was written. However, limited data were available to compare a tractor powered by a DDC Series 50 diesel engine under the same test cycle. The Series 50 engine is a 315-HP, four-cylinder version of the six-cylinder Series 60 engine, with the same production parts. It is a reasonable surrogate for the Series 60 diesel, in terms of emissions. Table 3-8 lists the averaged NOx emissions from the LNG tractor and a tractor with a 1997 DDC Series 50 diesel engine, over the Central Business District (CBD) test cycle. Figure 3-9 shows the speed versus time trace of the CBD and the (dyno roll) speed of the LNG tractor during one of the tests.

Photo 3-9. LNG Tractor #3 (cost shared by SCAQMD) during chassis dynamometer emissions testing at CaTTS (photo courtesy of CaTTS).

Table 3-8. Preliminary comparison of NOx emissions from diesel and LNG tractors tested at CaTTS over the Central Business District (CBD) Test Cycle

Test Vehicle	Engine / Fuel	Test Fuel	NOx (g/mile)
1986 GMC	'97 DDC Series 50	Diesel #2	27.4
1995 Freightliner FLD 120 (LNG Tractor #3)	Upgraded '95 DDC S60G	LNG	7.2
Testing for the LNG tractor was conducted at CaTTS on April 10, 2000. Testing for the diesel tractor was conducted at CaTTS on March 17, 1999. NOx data are the average of 3 tests for both vehicles. Particulate data were not yet available.			

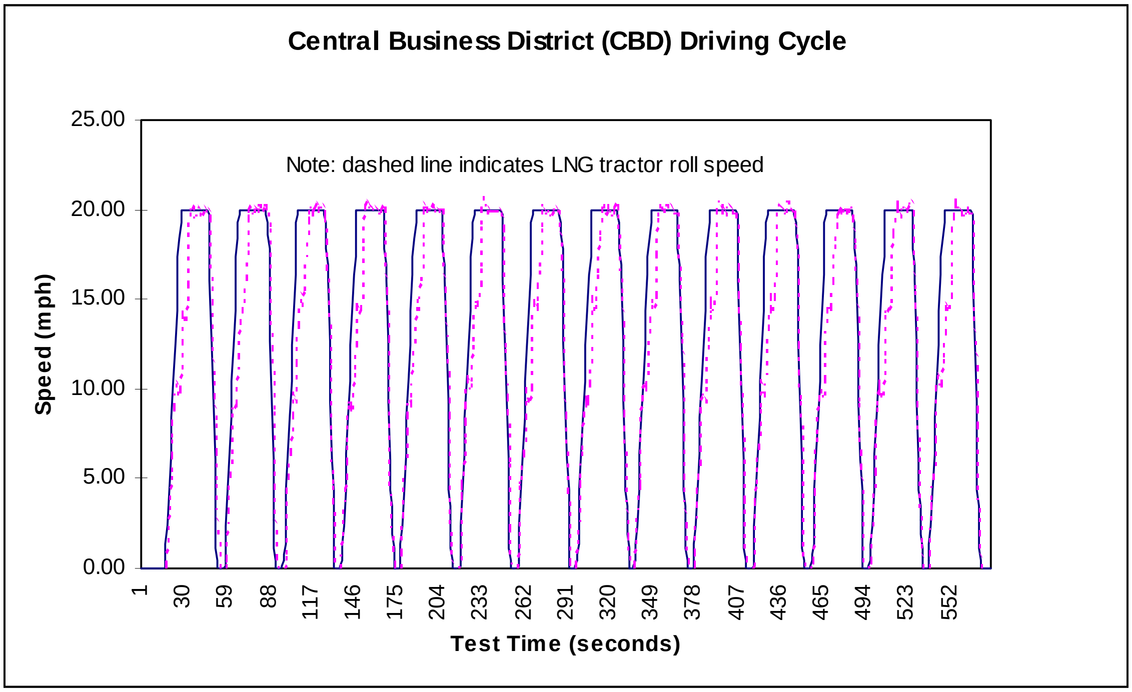

Figure 3-9. Roll speed of LNG tractor over CBD test cycle during CaTTS testing.

It is emphasized that these data are preliminary. Detailed data (all pollutants) for the LNG tractor and a comparable diesel are expected to be available for the final report under the CEC sister project. In general, the CaTTS testing on LNG Tractor #3 further corroborates the well-documented capability of heavy-duty natural gas engines to emit at least 50% less NOx than comparable diesel engines. However, the most important measure of the Series 60G emissions benefits will be future in-use emissions testing after the engine is commercially deployed in purpose-built LNG truck chassis, with state-of-the-art onboard fuel systems.

3.4 TASK 3 — LNG FUELING

One important objective of this project was to extend operation of the “Downtown Los Angeles” LNG station by approximately one year through government support, with the hope that it could gradually become more profitable, and therefore self sustainable. In mid 1996, a Jack B. Kelley Inc. affiliate known as Cryogenics Research & Development contracted with Mesa Pacific LNG, an affiliate of Southern California Gas Company, to lease the land adjacent to the NGV Ecotrans vehicle conversion facility near downtown Los Angeles. JBK then installed its Cryenco LNG fueling system on the property, featuring a 4,350 gallon LNG tank.

At the time of this installation, it was anticipated that the Downtown station would serve as the primary fueling location for a number of nearby heavy-duty fleets showing strong interest in using LNG buses and trucks. However, once the station was opened, the actual deployment of LNG vehicles occurred at a much slower rate than anticipated by the LNG industry and government advocates. Even by 1997 when planning began for the project described in this report, the number of LNG vehicles in Southern California was still very low, and only three LNG stations were on line. Under the project plan, the Downtown station was too far away from JBK’s depot in Fontana to serve as the primary fueling station for Tractor #1 (and later #2 and #3), but it would serve as a “secondary’ fueling option for JBK. Other heavy-duty fleets using LNG vehicles, such as Con-Way Trucking and ACE Hardware, were already occasionally using the Downtown station as a backup fueling facility.

However, it was clear that there would continue to be insufficient throughput at the Downtown LNG station to justify continued investment by the private sector. The other two LNG stations in Southern California – the United Parcel Services station in Ontario and the Taormina Industries station in Anaheim -- were at least experiencing regular use and moderate throughput. Thus, even though the Downtown station was strategically located for the future LNG fueling needs of many Southern California fleets, it was slated for closure by Mesa Pacific LNG and Cryogenics R&D unless government subsidies could be arranged.

Task 3 of the project was designed for exactly that purpose. In developing the project, ARCADIS Geraghty & Miller worked with SCAQMD staff, Mesa Pacific LNG and Cryogenics R&D to arrange to keep the station open for approximately one year longer than it would otherwise have been operational. The hope was that this would help the station survive its early low throughput problems and eventually become self sustaining as more LNG vehicles were deployed. Other objectives of Task 3 included 1) improving the Downtown LNG station’s accuracy in recording fuel fills, and 2) assisting JBK in troubleshooting general problems experienced during LNG fueling events.

Work performed in Task 3 and the various accomplishments are described below, in the context of specific subtasks.

Photo 3-10. The downtown Los Angeles Mesa Pacific LNG station

3.4.1 Subtask 3.1 – Station Subcontracts

ARCADIS Geraghty & Miller executed subcontracts with Cryogenics Research & Development and Mesa Pacific LNG to pay for 12 months of equipment and operations costs, respectively, for the station. As during the previous two years of operation, refueling events for LNG vehicles were extremely rare at the station during the extended period of operation. Even by 1999, the number of LNG-fueled trucks and buses in Southern California continued to be very low, and those vehicles that did exist tended to be located many miles from the downtown station. Thus, the station continued to have high operating costs and extremely low fuel throughput, so all parties agreed it would be closed after the period of extended operation.

3.4.2 Subtask 3.2 – LNG Refueling Training

This subtask required ARCADIS Geraghty & Miller to provide LNG refueling training for JBK staff, if necessary. JBK's Fontana depot employees were familiar with the use of LNG and correct fueling procedures because of JBK’s affiliation with ALT USA. However, ARCADIS Geraghty & Miller and DDC provided a review of LNG fueling procedures during the LNG training session conducted at the JBK depot in March 1999.

3.4.3 Subtask 3.3 – Fuel Dispensing Accuracy

Under Subtask 3.3, ARCADIS Geraghty & Miller inspected the downtown station in December of 1998 to locate information about certification requirements and product data for the dispensing flow meter. After searching the station, contacting JBK, and contacting the flow meter manufacturer, the meter was located on an insulated pipe (underneath the insulation). However, before efforts were completed in this subtask, the station was closed, eliminating the need to continue the investigation of the flow meter.

3.4.4 General Support for Fueling at the Ontario Station

As previously noted, the primary fueling station was the ALT USA facility located on the property of United Parcel Services at 1735 S. Turner Avenue in Ontario. ALT-USA owns and maintains this station. It was constructed in 1996 with funding from the San Bernardino Association of Governments (SANBAG) and SCAQMD. Some of the funding was provided through contracts with ARCADIS Geraghty & Miller in a previous project.[7] LNG fueling at the station began in March of 1998. This station includes an L/CNG facility that supplies CNG to UPS and the general public.[8] The LNG supply is used by JBK, UPS, ACE Hardware, and Con-Way Express, among other heavy-duty fleets. The design features of the station are described in Table 3-9.

Table 3-9. Design features of the Ontario UPS L/CNG fueling station.

Feature	Description
LNG storage tank	6,000 gallon double-walled, vacuum-insulated storage vessel, manufactured in 1995 by Minnesota Valley Engineering (Model HLNG-6000-NC-250). Insulated to achieve a normal evaporation rate less than 0.35% of tank capacity per day. Equipped with pressure building coils for bulk conditioning of contents to desired saturation pressure. Rated for a maximum working pressure of 250 psig.
LNG leak containment	Concrete tank pad is surrounded by a concrete block wall. Volume of the enclosure is sufficient to hold the tank's capacity of 6,000 gallons.
LNG dispensing pump	Single stage centrifugal pump, manufactured by ACD. Pump is rated to deliver 30 gpm with a pressure rise across the pump of 60 psi. Pump is driven by a 7.5-hp, 460V AC, 3-phase motor.
LNG flow totalizing	Micro-motion vibrating tube mass flow rate gauge
LNG dispensing nozzle	Parker-Hannefin Model 1169-60B
Vapor return nozzle	MVE
LNG control valves	Solenoid controlled, air actuated, manufactured by ACD. Service air is provided by a mechanical compressor located in the shed housing the site controller and water heater.

Source: Drexel LNG & CNG Systems, "Data Package for ALT/UPS LNG /LCNG Vehicle Fueling Facility, Ontario, California." June 1, 1997.

Throughout the project's duration of approximately 18 months, ARCADIS Geraghty & Miller provided assistance in resolving issues and problems related to refueling Tractor #1. For example, this station has been selected under SCAQMD and GRI funding to receive upgrades in

[7] The permitting, building and operation of this station has been documented in other projects, including one conducted by ARCADIS Geraghty & Miller for the AQMD. Copies of the final report can be obtained through the South Coast Air Quality Management District.

[8] An L/CNG station is an LNG station that captures natural gas vapor from the LNG system and compresses it into CNG.

the near future that will require it to shut down for an extended period of time. ARCADIS Geraghty & Miller investigated the timing for the upgrade to determine how JBK will fuel the LNG tractors during the station's down time. Ken Kelley of JBK indicated that this would be accomplished through a temporary mobile refueling set up. However, as of the writing of this report, GRI and SCAQMD have not established a definitive schedule for the station upgrade to take place.

Photo 3-11. Delivery of LNG to the Ontario station by a conventionally fueled JBK truck (photo by ARCADIS Geraghty & Miller).

3.5 TASK 4 — REPORTING

The primary objectives of Task 4 were: 1) to provide monthly progress reports (MPRs) to NREL and SCAQMD; 2) to arrange quarterly project meetings or teleconferences; 3) to provide real-time updates on project progress, 4) to provide copies of subcontracts executed under the project, and 5) prepare a final report for NREL and SCAQMD at the project's conclusion.

Over the life of the project, ARCADIS Geraghty & Miller executed four subcontracts and prepared 18 MPRs detailing the work performed and the progress achieved in the corresponding reporting period. Additionally, ARCADIS Geraghty & Miller provided ongoing realtime updates to the project sponsors. Table 3-10 summarizes the most significant efforts and accomplishments under Task 4, excluding subcontracts and the normal preparation of MPRs.

Table 3-10. Summary of work performed by ARCADIS Geraghty & Miller under Task 4 (excluding monthly progress reports)

Month	Work Performed
July ‘98	Internal project kickoff meeting
Aug ‘98	Memo summarizing problem at downtown LNG station
Sep ‘98	Project kickoff meeting (1^{st} Quarterly Progress Review)
Jan ‘99	2^{nd} Quarterly Progress Review Meeting
Jul '99	3^{rd} Quarterly Progress Review Meeting
Aug ‘99	Memo: Update on Emissions Certification
Jan ‘00	Initiated Draft Final Report
Feb '00	4^{th} Quarterly Progress Review Meeting
April ‘00	Submitted Draft Final Report
May ‘00	Completed and submitted Final Report

4. PROJECT COST ANALYSIS

The total direct funding contributions to this project from SCAQMD and DOE/NREL are summarized in Table 4-1. Further descriptions of how funds were allocated are provided below.

Table 4-1. Total direct project funding, by task.

Task #	Key Task Elements	SCAQMD Contract #98068	DOE/NREL Contract #ACI-6-16627-01*	All Funding
0	• Engine Upgrade for Tractor #1 • Cost sharing of DDC field support for Tractor #1	$0	$28,000	$28,000
1	• Demonstration and field support for Tractor #1 • Cost sharing of engine upgrades for Tractors #2 and #3 (CEC sister project)	$128,405	$0	$128,405
2	• Document emissions certification • Facilitate chassis dyno emissions testing	$14,195	$0	$14,195
3	• Support equipment and operational costs of Downtown LNG station • Assist in LNG fueling logistics for JBK	$136,472	$0	$136,472
4	• Monthly progress reports, quarterly project review meetings, and final report • Real-time updates	$37,094	$0	$37,094
Total Budget and Funding		$316,166	$28,000	$344,166

* The DOE/NREL-funded work was part of a larger NREL contract, which began in 1996 and included funding for an early-generation DDC Series 60G engine. The $28,000 of DOE/NREL funding shown in this table was set aside to cost share the SCAQMD project, which came later. Task 0 above is analogous to Task 3 of the NREL-ARCADIS Geraghty & Miller contract. It has been renumbered here to clarify the funding contributions of SCAQMD and DOE/NREL specifically for this project, i.e., the JBK demonstration of LNG tractors with the upgraded DDC Series 60G engine.

4.1 DOE/NREL Funding (Task 0)

As indicated in Table 4-1 above, DOE/NREL provided $28,000 towards the engine upgrade that was performed by DDC on LNG Tractor #1, and DDC's subcontract to provide field support during the 12-month demonstration.

4.2 SCAQMD Funding (Tasks 1-4)

Table 4-2 provides a break down of how SCAQMD funding was allocated for the project, by task expenditures.

Table 4-3 shows how SCAQMD funding was allocated by cost category. Figure 4-1 shows the rate at which SCAQMD funds were spent over time compared to the original project timeline.

Table 4-2. SCAQMD contract budget and expenditures, by task.

Task	Task Budget ($)[9]	Expenditures ($)	Variance ($) (=Budget–Expenditures)	% Complete
Task 1 – Field Demonstration	$128,405	$128,440	-$35	100%
Task 2 – Emission Testing	14,195	14,137	58	100%
Task 3 – LNG Fueling	136,472	136,468	4	100%
Task 4 – Reporting	37,094	37,081	13	100%
Total Project	**$316,166**	**$316,126**	**$40**	**100%**

Table 4-3. SCAQMD contract budget and expenditures, by cost category

Cost Category	Budget ($)	Expenditures ($)	Variance ($) (=Budget – Expenditures)
ARCADIS G&M Labor	117,075*	117,922	-847
Travel and ODC	5,224*	4,472	852
Subcontracts	193,867	193,831	36
Total Project	**$316,166**	**$316,125**	**$40**

***The budget for AG&M labor was increased by $1,000 and the budget for Travel and ODC was decreased by $1,000 – per written authorization by SCAQMD's project officer.

[9] Refers to the budget as amended for the addition of Subtask 1.6.

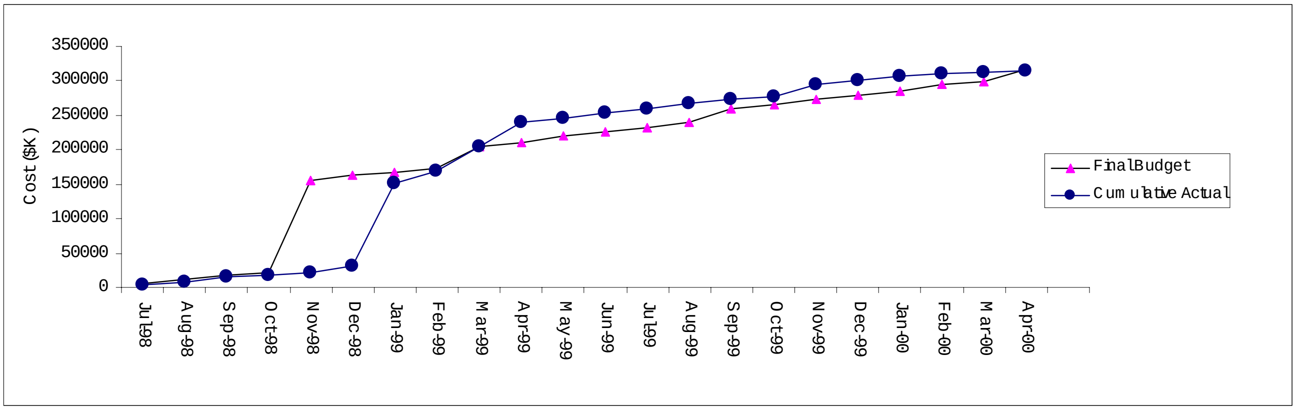

Figure 4-1. Expenditures of SCAQMD funding as a function of the project timeline.

4.3 Project Cost Sharing

Extensive in-kind cost sharing was provided for this project, easily exceeding 50% of the total project cost. Examples of efforts that were cost shared by the project's various industry participants include the following:

- DDC's efforts to certify the LNG-fueled 400 horsepower version of the Series 60G engine to California's optional low-NOx emissions standards
- DDC's extensive efforts to support Tractor #1, beyond the amount of compensation offered in its subcontract
- JBK's extensive incremental time costs to fuel, operate and maintain the LNG tractor
- JBK's donated time to deliver the truck to various special events and workshops
- JBK's donated time to attend quarterly project review meetings and make executive decisions about the project
- JBK's generous offer to make Tractor #3 available for three weeks of emissions testing at the CaTTs laboratory
- VDDA's extensive donated time to work on the tractors, beyond compensation received as a subcontractor to DDC and ARCADIS Geraghty & Miller
- PG&E's funding of the chassis dynamometer emissions testing conducted at CaTTs.

5. CONCLUSIONS AND RECOMMENDATIONS

Nearly all of the objectives and goals for this project (as previously described) were successfully met or exceeded. Accomplishments, conclusions and recommendations from this project are further discussed below by various categories.

5.1 Emissions Benefits

- This project has corroborated other existing certification and chassis dynamometer emissions data, which have shown that LNG engines offer major NOx and PM emissions reductions compared to equivalent diesel engines.

- DDC's certification of the upgraded S60G engine at 400 hp and 1450 lbs-ft of torque to California's optional low-NOx emissions standards is a major accomplishment. Significant deployment of LNG trucks in the heavy-duty sector may follow in the near future. The funds provided by SCAQMD and DOE/NREL to make this project possible were instrumental in DDC's achievement.

- Based on preliminary data from the CaTTS testing, it is estimated that LNG Tractor #1 emitted between 50% and 80% <u>less</u> NOx during its 47,000 mile demonstration than would be emitted by a comparably sized, fully electronic diesel-fueled tractor over the same mileage and duty cycle. The total mass of NOx emissions that were avoided through the use of the Series 60G engine are conservatively estimated at between 1,000 and 1,800 pounds.

5.2 Fuel Stations and Fueling Logistics

- The use of project funds to support the Downtown LNG station served its short-term objective, by allowing the station to remain operational for approximately one year longer than it would otherwise have lasted. However, the longer-term goal was not achieved, i.e., delaying the pending closure of the station until profitable demand for LNG developed.

- The downtown LNG station is an example of an alternative-fuel facility that was built in a strategic location for potential sustainable operation, but the anticipated AFV anchor fleets did not come to fruition. Throughput at such stations is so low that private-sector funding usually cannot be sustained. Low throughput is the biggest barrier to expanding the LNG infrastructure, which in turn is the biggest barrier to widescale deployment of LNG vehicles in Class 8 trucking applications.

- Until this classic "chicken and egg" problem is resolved with LNG stations and vehicles, it may be necessary for trucking fleets to share LNG fueling facilities with transit districts that are aggressively moving forward with LNG buses, such as the

Orange County Transit Authority.

- Running out of fuel (usually requiring towing) remains a significant problem for LNG trucks, due to the paucity of LNG stations and the following other factors: reduced vehicle range due to lower volumetric energy content of LNG; less accurate fuel gauges; the lack of extensive driver experience with LNG; the difficulty of getting cold fuel into relatively hot tanks with high vapor pressure; and the not-uncommon need to vent and service an LNG truck's onboard fuel system at a location remote from the nearest fueling station. Some of these issues require technical solutions (e.g., improved and larger on-board LNG storage tanks), while others involve institutional ones (e.g., improved training of end users).

- While mobile LNG fuelers have been developed by companies such as ALT USA, there currently is no readily available, practical way to fuel a stranded truck with LNG.

5.3 LNG Engine Technologies

- This demonstration marked the first use in California of a dedicated natural gas truck with the high horsepower and torque needed to compete in Class 8 trucking applications. This project was very successful as an essential step towards full commercialization of dedicated LNG tractors with upgraded, low-NOx DDC Series 60G engines.

- The upgraded S60G engine in Tractor #1 performed extremely well over most of the 12-month demonstration. High engine oil consumption caused by a pinched ring in one of the cylinders was the only significant problem through the first 47,000 miles. However, driveability problems were encountered late in the demonstration, and more work will be needed in the follow-on demonstration funded by CEC to address these problems.

- The S60G engine in Tractor #1 delivered relatively good fuel economy for a spark-ignited natural gas engine, achieving about 80% of the efficiency of the diesel control tractor. However, additional work is needed to improve heavy-duty natural gas engine efficiency and fuel economy. Work of this nature is already underway or planned, through other government-funded programs.

5.4 Economics and Institutional Barriers

- For LNG to succeed as a fuel in Class 8 trucking applications, strong corporate commitments are essential from the host fleets, the fueling station providers, and the engine/chassis manufacturers.

- An essential element of LNG's potential for widespread application in Class 8 trucking is very high fuel consumption, which can lower fuel costs and help to offset the added cost of the alternative fuel vehicle.

- Comprehensive training on operational and safety issues is essential and will pay for itself in the long run.