National Renewable Energy Laboratory
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Heavy-Duty Waste Hauler with Chemically Correct Natural Gas Engine Diluted with EGR and Using a Three-Way Catalyst

Final Report
February 24, 2004 – February 23, 2006

Subcontract Report
NREL/SR-540-38222
September 2005

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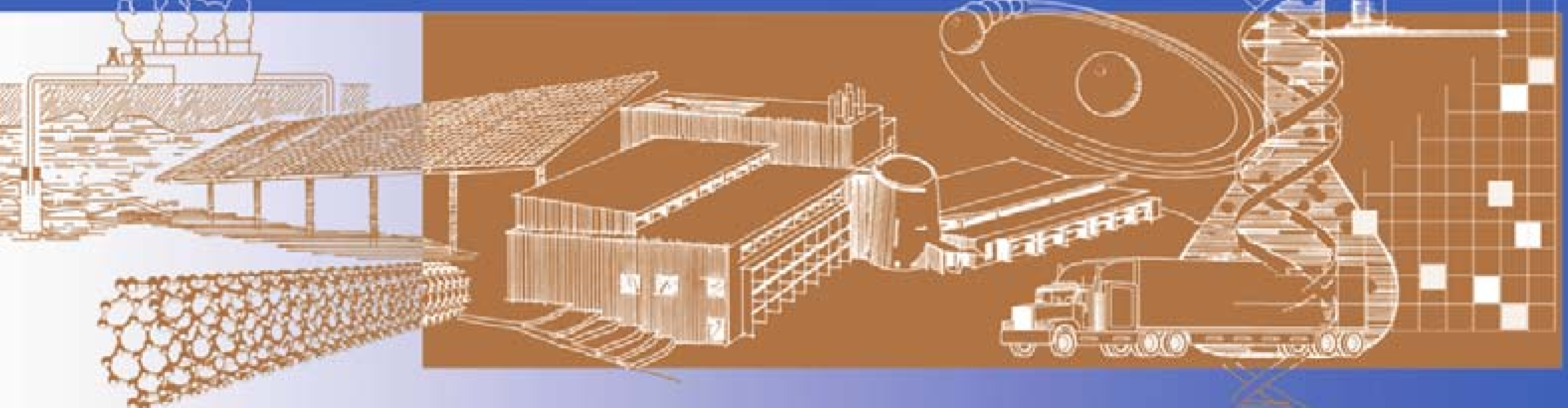

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

AFR	air to fuel ratio
AI	Application Specific Emissions Technology – Internal Exhaust Gas Recirculation
AQMD	South Coast Air Quality Management District
ASET®	Application Specific Engine Technology
BHP	brake horsepower
BMEP	brake mean effective pressure
BSCO	brake specific carbon monoxide
BSEC	brake specific energy consumption
BSFC	brake specific fuel consumption
BSHC	brake specific hydrocarbons
$BSNO_x$	brake specific nitrogen oxides
BTDC	before top dead center
BTE	brake thermal efficiency
Btu	British thermal unit
CAN	controller area network
CFR	Code of Federal Regulations
CMCAC	chassis mounted charge air cooler
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
deg	degree
DF	deterioration factor
DPF	diesel particle filter
ECU	engine control unit
EGR	exhaust gas recirculation
ESC	European Stationary Cycle
FMV	fuel metering valve
FTP	Federal Test Procedure
g/bhp-hr	grams per brake horsepower hour
GC	gas chromatograph
HC	hydrocarbons
k	kilo
LNG	liquefied natural gas
MAP	manifold absolute pressure
MHz	megacycles per second (megahertz)
MR	Mack refuse
NMHC	nonmethane hydrocarbons
NO_x	nitrogen oxides
NREL	National Renewable Energy Laboratory
NTE	not-to-exceed
O_2	oxygen
PCM	powertrain control module
PM	particulate matter
psi	pounds per square inch

PtHP	pre-throttle pressure
rpm	revolutions per minute
SwRI	Southwest Research Institute
THC	total hydrocarbons
UEGO	universal exhaust gas oxygen (sensor)
VGT	variable geometry turbocharger

EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) funds research and development that reduces U.S. dependence on imported petroleum and promotes better air quality. Natural gas vehicles help to diversify automotive fuel requirements. In addition, natural gas engines and vehicles have led the way to lower exhaust emission requirements. The work described in this report was supported through DOE's National Renewable Energy Laboratory (NREL).

NREL and the South Coast Air Quality Management District (AQMD) through separate agreements are funding a program with Mack Trucks Inc. to develop the next generation heavy-duty natural gas engine to be installed in a refuse hauler over two years. Mack and Southwest Research Institute developed the E7G 12-liter lean burn natural gas engine to operate with stoichiometric (chemically correct) combustion and cooled exhaust gas recirculation (EGR). This engine was coupled to a three-way catalyst for reducing emissions. The objective of the project is to develop the natural gas engine with nitrogen oxide (NO_x) and particulate matter (PM) emissions of 0.5 g/bhp-hr and 0.01 g/bhp-hr respectively with the use of a three-way catalyst. Year one of the project was to develop the Woodward OH2.0 control system for stoichiometric operation and to control EGR. The second year, which is funded through the AQMD, will run two refuse trucks on the Mack E7G with a three-way catalyst during normal operation and service near Los Angeles for six months. Waste Management is participating as a partner with Mack and will operate the trucks in CA. Waste Management currently operates the largest natural gas fleet of 400+ vehicles in the United States with the majority using the Mack E7G lean burn engine. The purpose is to demonstrate the commercial potential of the three-way catalyst coupled to a heavy-duty natural gas engine for reducing emissions and demonstrating that natural gas engines can meet 2007 and 2010 emissions without major engine modifications. During year two, a 1500-hour durability test is scheduled to determine the emissions deterioration factor (DF) for the engine and three-way catalyst.

Year one of the two-year project is complete with the successful development of the Mack E7G engine with a three-way catalyst. The emissions measured on the U.S. Federal Test Procedure were with a de-greened, three-way catalyst at 0.049g/bhp-hr NO_x, 0.002 g/bhp-hr PM, 0.435 g/bhp-hr THC, 0.000 g/bhp-hr NMHC, and 4.153 g/bhp-hr CO. The brake specific fuel consumption was 2% above the current lean burn engine calibrated at 2.0 g/bhp-hr NO_x. The engine torque calibration was also increased from 1050 lb-ft at1250 rpm to 1180 lb-ft at 1250 rpm. Rated power remained unchanged at 325 hp, 1950 rpm. The components were also fabricated to integrate the cooled EGR system and variable geometry turbocharger onto the Mack lean burn E7G. The two prototype engines for the demonstration phase were also built.

1.0 INTRODUCTION

The U.S. Department of Energy's (DOE) FreedomCAR and Vehicle Technologies Program is advancing the development of gaseous-fueled internal combustion engines, which have the potential to reduce U.S. dependence on imported petroleum and improve air quality. Natural gas is an abundant energy source in this country that can be used as an automotive fuel. With rising fuel prices, many companies are seeking alternatives to imported oil to help offset fuel costs. However, only a small portion of vehicles are powered by natural gas and mainly operated by local state municipalities. DOE's National Renewable Energy Laboratory (NREL), led by the Center for Transportation Technologies and Systems, has the goal to help industry introduce alternative fueled vehicles into the marketplace by working with public and private organizations to develop and demonstrate innovative technologies to help reduce the nation's dependence on imported oil. California has perhaps the most aggressive programs to help reduce pollution and curb the use of imported oil. Stringent fleet rules in California require that whenever public fleet operators with 15 or more vehicles replace or purchase new ones, they should be alternative fueled vehicles. NREL is leading the effort to develop the next generation heavy-duty natural gas engine to help reduce emissions in non-attainment areas.

Emissions standards are also becoming increasingly stringent across the United States. Standards for 2007 require that nitrogen oxides (NO_x) emissions be reduced from the current 2.5g/bhp-hr to a phase-in level of 1.18 g/bhp-hr with particulate matter (PM) emissions less than 0.01 g/bhp-hr. Meeting the PM emission standard with diesel will require the use of a diesel particulate filter (DPF) and heavy exhaust gas recirculation (EGR) rates for NO_x control. The NO_x standard for 2010 becomes 0.2g/bhp-hr for all heavy-duty engines. For the diesel engine to meet that standard, new technology in the development of NO_x after treatment will be required in addition to even higher EGR levels. Natural gas engines have an advantage over diesel in that they operate on a gaseous fuel and are typically spark ignited, which emits lower PM by nature. This allows the combustion to operate at or near stoichiometric air to fuel ratio (AFR), and maintain high tailpipe exhaust temperatures over the duty cycle as compared to a diesel engine. This will allow a three-way catalyst to be coupled to the exhaust to oxidize carbon monoxide (CO) and hydrocarbon (HC) emissions, and reduce NO_x emissions.

Three-way catalyst technology was developed in the 1970s for the automobile industry to clean up the emissions from the gasoline engine. It also proved to be the most cost-effective solution. Since then, three-way catalyst technology has evolved and demonstrated extremely low CO, HC, and NO_x emissions for the auto industry, which allows even lower emitting vehicles to be manufactured. Operating a heavy-duty, natural gas engine with a three-way catalyst does not require any special hardware in that proven control systems and sensors used for the light-duty industry can be applied to the heavy-duty, natural gas engine as demonstrated with current lean burn engines. EGR, however, will need to be added for knock and exhaust temperature control as stoichiometric operation inherently increase the engine out exhaust temperatures. Applying three-way catalyst technology to a heavy-duty, natural gas engine leverages 35+ years of development as applied to light-duty gasoline engines. The application also will be a very cost-effective solution for meeting future emissions standards. Mack Trucks Inc. is the leader in heavy-duty, natural gas engines for use in the refuse industry. Waste Management is the leader in natural gas refuse haulers and operates a fleet of 400+ natural gas refuse haulers in southern California.

NREL and the South Coast Air Quality Management District (AQMD), through separate and contingent critical path agreements, are funding a program with Mack to develop a next generation, stoichiometric heavy-duty refuse hauler with a three-way catalyst. The engine is based on the Mack E7G lean burn engine currently in production. The program was designed to last over two years with the first year for engine development. During the second year, a prototype engine with a three-way catalyst will be installed in two Waste Management refuse haulers, which will be operated in the Los Angeles basin for six months. Waste Management is committed to finding alternative fuels and reducing pollution in non-attainment areas. A 1500-hour durability test is also scheduled to determine the emissions deterioration factor (DF) for the engine, and three-way catalyst emissions and component durability.

1.1 Project Objective

The project's objective for the first year was to develop a low emissions natural gas engine. The emissions targets for this project are 0.5 g/bhp-hr of NO_x and 0.01 g/bhp-hr of PM. To meet the objective, a stoichiometric (chemically correct) combustion natural gas engine with exhaust gas recirculation (EGR) and a three-way catalyst has been developed. Although the NO_x target is 0.5 g/bhp-hr, the development objective is for NO_x emissions to achieve the 2010 standard of 0.2 g/bhp-hr.

For an engine to meet the 2010 emission standards, exhaust after treatment will likely be necessary. Along with an efficient and reliable engine, an after-treatment system with improved performance, cost-effectiveness, reliability, and simplicity is desirable. To meet these objectives, a stoichiometric combustion natural gas engine with EGR and a three-way catalyst was developed.

The stoichiometric combustion allows for the use of a three-way catalyst. The effectiveness of a three-way catalyst depends on an engine running at or near the stoichiometric mixture for combustion. The three-way catalyst can simultaneously reduce NO_x emissions, and oxidize HC and CO emissions (including toxic emissions and natural gas engine particulates) when the engine is operating with the chemically correct mixture. To improve the efficiency of this engine, high rates of EGR will be used. The EGR acts as a dilutant just as excess air does in a lean burn engine. The EGR will lower combustion chamber temperatures, improve efficiency, lower engine out NO_x emissions, and reduce the tendency to knock.

The project's major tasks include:

- Engine development
- Initial emissions testing
- Building two prototype engines
- Durability testing
- Final emissions testing
- Field testing.

This report only covers the first three tasks.

2.0 TECHNICAL DISCUSSION/RESULTS

A Mack E7G engine was modified for stoichiometric operation with high rates of EGR. A new engine control system was installed on the engine. The EGR system used on the diesel version of the engine was modified for the gas engine. Emissions tests were conducted.

ENGINE DESCRIPTION

The engine was developed from the current production Mack E7G lean burn natural gas engine. Components were added and/or modified to install the cooled EGR and the Woodward OH 2.0 control system. The engine specifications are listed below. Note that the engine was designated the E7GT to distinguish the three-way catalyst version from the lean burn version.

ENGINE

- Mack E7GT 12 liter (728 ci) displacement 6-cyl inline
- Bore x Stroke = 4.875" x 6.5"
- 325 bhp@1950 rpm
- Peak torque: 1180 lb-ft@1250 rpm
- Turbocharger: Holset HY 40V VGT. Water-cooled bearing housing
- Low-pressure, cooled EGR with CMCAC (chassis mounted charge air cooler)
- Compression ratio = 11.5:1
- Idle speed = 650 rpm
- High idle = 2150 rpm
- Spark plugs: 6 - Champion RX85PYP
- Ignition System – Woodward "Heavy-Duty Smart Coil"
- Cooled EGR: Lisk control valve
- Closed-loop EGR control via Bosch universal exhaust gas oxygen (UEGO) sensor

FUEL SYSTEM

- Woodward Flo-Tech™ "drive by wire" throttle control. Min Max automotive type
- Servojet (SP021) natural gas injectors, 8 total
- Mack developed air / natural gas mixing ring and elbow
- Woodward OH2.0 controller, CAN/J1939
- Stoichiometric, Closed–Loop
- Fuel = LNG, CNG
- Fuel pressure set point = 100-120 psi

AFTER TREATMENT

- Englehard LEX-120 Pt:Pd:Rh (1:28:1) @250 g/ft^3
- Mounting distance from turbo outlet = 44.8 in
- Test catalyst size: d=10.5in, Length = 6in, Volume = 17 liters

2.1 Engine Modifications

The Mack E7G is a lean burn, natural gas fueled engine. This engine uses the Woodward On-Highway Version 1.2 (OH1.2) engine control system. This engine was modified for stoichiometric operation with cooled EGR. In addition, Version 2 of the Woodward On-Highway (OH2) engine control system was used.

2.1.1 EGR System

The diesel EGR system was used as a basis for the natural gas system. This system was modified as described below for the natural gas engine.

2.1.1.1 Diesel EGR System

The cooled EGR system started with the system used on the current Mack E7 diesel engine. This cooled EGR system is used in highway-series trucks.

Figure 1 shows a schematic of a high-pressure EGR loop. A Variable Geometry Turbocharger (VGT) is used to control exhaust pressure, which drives the EGR through the high-pressure loop. One of the advantages of the high-pressure loop is the quick response time of the EGR loop. A disadvantage is that the exhaust pressure needs to be higher than the intake pressure so that the EGR can flow. The original diesel EGR system used an inline flow meter, which was removed for the natural gas engine. Other methods were used to determine the EGR flow and EGR rates, which are described in the Engine Development section.

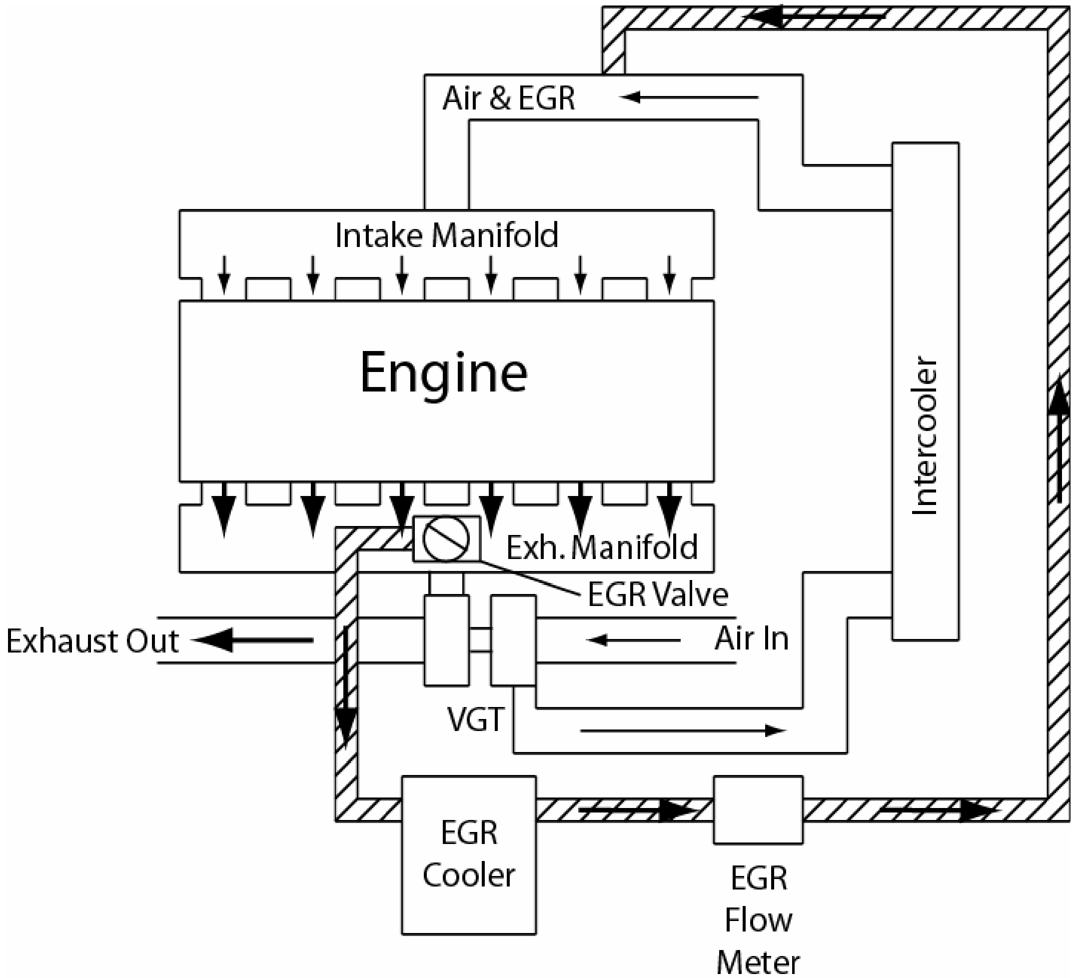

FIGURE 1. HIGH-PRESSURE EGR LOOP

2.1.1.2 Initial Natural Gas EGR System

The initial configuration of the natural gas engine was a low-pressure EGR loop. A low-pressure loop should produce higher efficiency since the intake manifold pressure can be higher than the exhaust pressure.

Figure 2 shows a schematic of a low-pressure EGR loop. The VGT from the diesel engine was used for the natural gas engine. This VGT was sized to operate with part of the engine exhaust flow going through the turbine of the turbocharger with the other part going through the EGR loop. With the low-pressure loop, all of the exhaust flow goes through the turbine of the turbocharger. With all of the exhaust going through the turbocharger, full power was achieved at approximately 40% throttle with the vanes on the turbocharger fully open. In this configuration, the turbocharger produced too much boost and did not provide any means for reducing the intake manifold pressure and could lead to turbo wheel over speed.

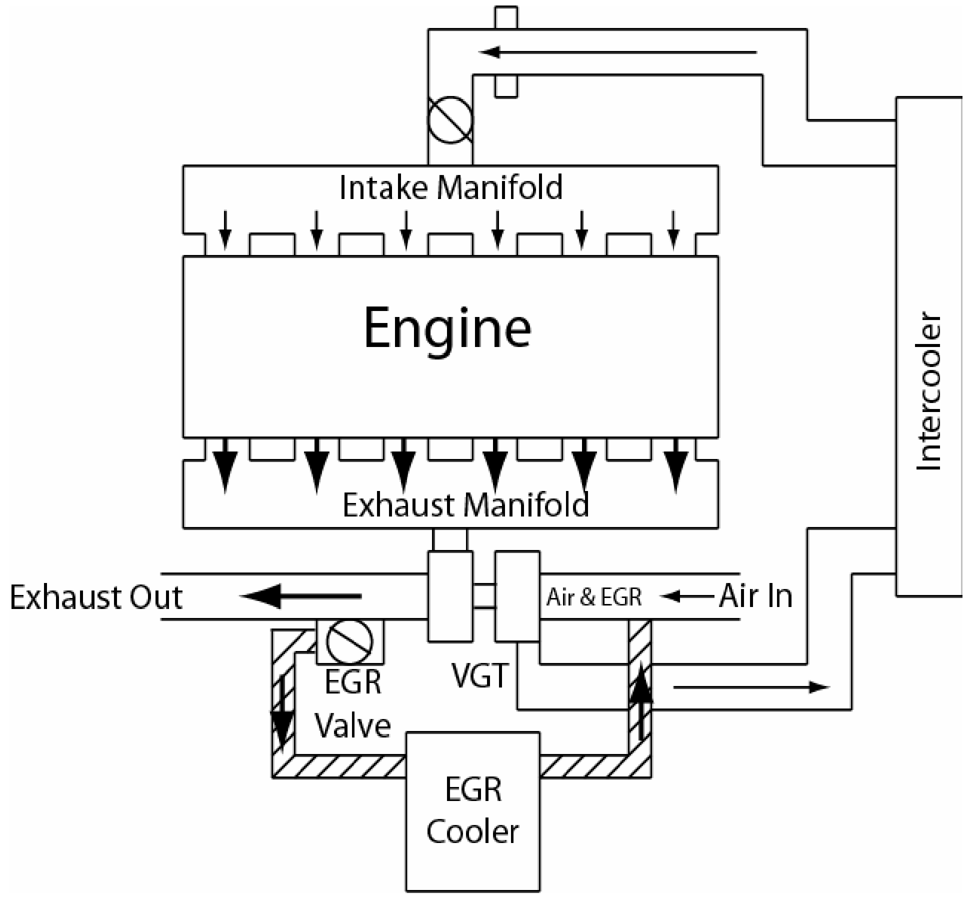

FIGURE 2. LOW-PRESSURE EGR LOOP

2.1.1.3 Final Natural Gas EGR System

The EGR system was then changed to a high-low pressure loop. Figure 3 shows a schematic of a high-low pressure EGR loop. In this configuration, the turbocharger does not over boost the engine, and the intake manifold pressure can be higher than the exhaust manifold pressure.

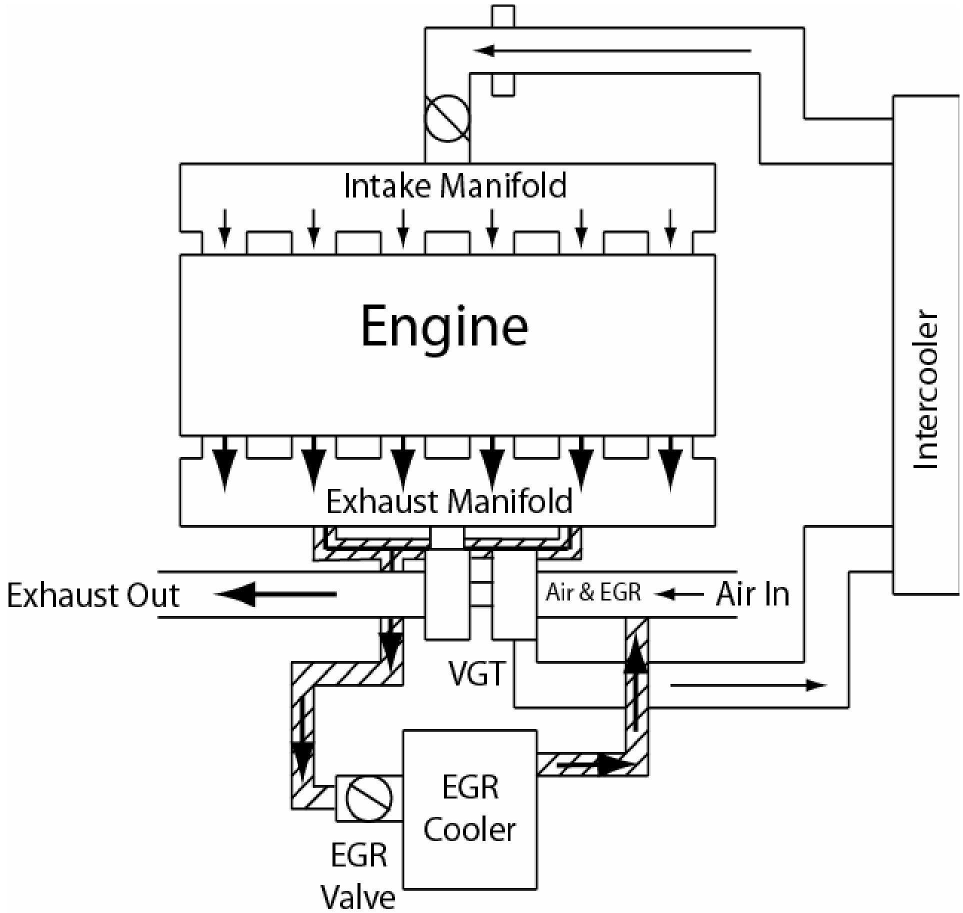

FIGURE 3. HIGH-LOW PRESSURE EGR LOOP

The exhaust comes from the bottom of the manifold, which allows the engine to fit into the refuse hauler chassis. Exhaust is taken from both sides of the divided exhaust manifold so that the exhaust manifold pressure on the front and back cylinders are similar. Changing the exhaust manifold pressure changes the residual fraction (which becomes internal EGR), which changes the amount of external EGR a cylinder can tolerate before misfiring. Taking exhaust from only one side of the exhaust manifold results in too much pressure on the other side of the manifold, which does not allow for the optimal EGR in all cylinders.

2.1.2 Engine Control System

For this natural gas engine, the Woodward OH2.0 engine controller was selected. The original Mack E7G engine uses the Woodward OH1.2 engine controller, which has more limitations than the OH2. Table 1 shows some differences between the engine controllers.

TABLE 1: DIFFERENCES BETWEEN THE WOODARD OH2.0 AND OH1.2

Item	OH2.0	OH1.2
Processor	MPC565	HC12
Clock Frequency	56 MHz	12 MHz
Instructions/Clock	1	0.25
Data Bus Width	32 bits	8 bits
Flash Memory	1 Mb	60 kb
Static Random Access Memory	36 kb	2 kb
Controller Area Network (CAN) Support	Full	Limited
Programming	Floating Point C Code	Fixed Point Assembly Code
I/O	128 Pin	60 Pin
Ignition System	Individual smart coils controlled directly by the OH2.0	Coil-on-plug with the OH1.2 controlling a separate Ignition Control Module

Since the OH2.0 is a new engine controller both for Woodward and for the Mack engine, troubleshooting and debugging continued throughout the engine development and emissions testing tasks. Woodward developed control algorithms for the OH2.0 as a lean burn engine, which served as a basis for the stoichiometric engine with EGR. Converting to a stoichiometric engine was a simple calibration change of the equivalence ratio table in the OH2.0. Adding the external EGR required new control algorithms. The Southwest Research Institute (SwRI) developed the algorithms for the EGR control and Woodward developed the program for downloading in to the OH2.0. Table 2 shows some features of the EGR control algorithms.

TABLE 2: EGR CONTROL SYSTEM

Item	Description
Open-Loop EGR Flow	The open-loop EGR flow was calculated using the pressure differential across the EGR system, the EGR density, and EGR valve position. • The pre-turbine pressure and an estimated inlet restriction were used to get a pressure differential across the EGR system. • The EGR density was calculated using the pressures and an estimated exhaust temperature. • The EGR valve was calibrated for flow coefficient and area versus valve position.
Closed-Loop EGR Flow	The closed-loop EGR flow was controlled with a UEGO sensor in the intake system between the turbocharger and the intercooler. • The UEGO sensor is shielded to limit the heat loss under high flow rate conditions. • The UEGO sensor measures the oxygen concentration of the air and EGR mixture. • The oxygen concentration can be used to determine the percentage of EGR.
Limited EGR Rates	The EGR can be limited under certain conditions. • EGR rate can be limited based on ambient humidity and compressor inlet temperature to prevent water from dropping out before the turbocharger • EGR rate can be limited based on ambient humidity, manifold air temperature, and manifold air pressure to prevent water form dropping out in the intake manifold
Cold Start	The EGR rate is reduced at low engine coolant temperatures. This prevents water from dropping out in the air-EGR mixture anywhere in the system and assists with catalyst warm up.
Manifold Air Pressure	The manifold air pressure is appropriately modified to maintain constant power when the EGR rate is reduced or limited.
Ignition Timing	Igniting timing is modified when the EGR rate is reduced or limited.
Airflow Calculation	The airflow calculation is appropriately modified when the EGR rate is reduced or limited.

2.2 Engine Development

Engine development was conducted in a steady-state test cell.

2.2.1 Test Cell Description

The steady-state test cell uses an eddy current dynamometer to absorb power. A heat exchanger is used for the engine coolant, where the engine out coolant temperature is controlled to a specified temperature. A heat exchanger is also used for the intercooler, where the intercooler out temperature is controlled. Natural gas was used for the testing, where it is compressed into a storage tank, and then delivered to the test cell where regulators reduce the pressure to a specified level (110-120 psi). A gas chromatograph (GC) records the gas composition on an hourly basis. Table 3 shows the average gas composition during the engine development along with the standard deviation.

TABLE 3: AVERAGE GAS COMPOSITION AND STANDARD DEVIATION FOR DEVELOPMENT WORK

Component	Concentration (vol %)	Standard Deviation
Methane	96.21	0.53
Ethylene	0.00	0.00
Ethane	1.76	0.23
Propane	0.22	0.08
Butanes	0.08	0.04
C5+	0.06	0.03
Carbon Dioxide	0.86	0.12
Nitrogen	0.81	0.15
Hydrogen Sulfide	0.00	0.00

Data were recorded with the SwRI data acquisition system. Table 4 shows the data recorded. All equipment was calibrated according to SwRI Standard Operating Procedure for Calibration and Maintenance.

TABLE 4: DATA RECORDED

Misc	Run Number Date Time # of Points Averaged Engine Speed Torque Fuel Flow Airflow Relative Humidity	Calculated	BTE BSFC BSEC BMEP Power Air Fuel Ratio Equivalence Ratio Fuel H/C Ratio Fuel O/C Ratio Fuel N/C Ratio Stoich Air Fuel Ratio Fuel Molecular Weight Fuel High Heating Value Fuel Low heating Value Reactive H/C Ratio Specific Humidity EGR Rate
Pressure	Fuel Barometric Inlet Restriction Boost Before Intercooler Boost After Intercooler Intake Manifold Pre-Turbine Exhaust Restriction Oil Gallery	Temperature	Coolant In Coolant out Fuel Ambient Air Boost Before Intercooler Boost After Intercooler Compressor Inlet Intake Manifold Exhaust Stack Individual Exhaust (6) Pre-Turbine Oil Gallery Oil Sump
Fuel Composition	Nitrogen Methane Carbon Dioxide Ethane Hydrogen Sulfide Propane Iso-Butane Butane Iso-Pentane Pentane Hexanes Heptanes Octanes Iso-Nonanes Ethylene	Emissions Emissions Calculations	CO HC NO_x CO_2 O_2 Intake CO_2 (for EGR) BSCO BSHC $BSNO_x$ Corrected $BSNO_x$ Equivalence Ratio EGR Rate

2.2.2 Engine Calibrations

The initial calibration for this engine was based on the Mack E7G lean burn gas engine. Some features of the lean burn engine are equivalence ratios of less than 1.00 and fuel shut off (open-loop operation) during decelerations. Calibrations specific for the stoichiometric engine include the following:

- The equivalence ratio table was set for 1.00 at all speeds and loads.
- The fuel shut-off was disabled in the calibration, and the program was changed to stay in closed-loop fueling during the decelerations.
- The flow constant and area for the EGR valve was calibrated to give the correct valve position for the EGR desired.
- The oxygen concentration in the intake system as calibrated for the correct EGR rate.
- The throttle table was calibrated to command a 75% throttle at a 100% foot pedal position at the higher speeds to reduce maximum intake manifold pressure.

Ignition timing and EGR rate sweeps were conducted on the engine on a 22-mode test with the exception of mode 1, which is the idle test point. At idle, the EGR valve will be closed. The 22-mode test is a combination of the 13-mode, steady-state test, also known as the European Stationary Cycle (ESC) or Organisation Internationale des Constructeur D'Automobiles test, and the SwRI 16-mode test. The 13-mode test is used for engine certification. The 16-mode test was developed to cover some of the areas that the 13-mode does not, such as light loads (<25% load) and/or low engine speeds (< peak torque speed). These are typically the areas where the calibration could change significantly from higher speed and load points. The test points are shown in Table 5 and Figure 4. Speeds have been rounded to a convenient test point. The speeds for the 16-mode and 22-mode test points are based on a more typical low speed at idle (650 rpm) and a more typical high speed at rated power (1950 rpm). The 13-mode speeds are based on the Code of Federal Regulations (CFR), which defines the low speed as the lowest engine speed where 50% of the maximum power occurs and the high speed as the highest engine speed where 70% of the maximum power occurs. The 25% speed, as defined for the 13-mode, is typically the same as the more typical 50% speed or peak torque speed of the engine. The 75% speed, as defined for the 13-mode, is typically the same as the more typical 100% speed or peak power speed of the engine.

TABLE 5: STEADY-STATE TEST POINTS

22 Mode	Speed *	Load	Speed (rpm)	Torque (ft-lb)	16 Mode	13 Mode	Speed for the 13 Mode **
1	0%	0%	650	160	1	1	idle
2	15%	15%	800	120	2		
3	15%	50%	800	400	3		
4	15%	100%	800	800	4		
5	30%	15%	1000	150	5		
6	30%	50%	1000	500	6		
7	30%	100%	1000	1000	7		
8	50%	15%	1250	188	8		
9	50%	25%	1250	313		7	25%
10	50%	50%	1250	625	9	5	25%
11	50%	75%	1250	938		6	25%
12	50%	100%	1250	1250	10	2	25%
13	75%	15%	1600	240	11		
14	75%	25%	1600	400		9	50%
15	75%	50%	1600	800	12	3	50%
16	75%	75%	1600	1200		4	50%
17	75%	100%	1600	1600	13	8	50%
18	100%	15%	1950	293	14		
19	100%	25%	1950	488		11	75%
20	100%	50%	1950	975	15	13	75%
21	100%	75%	1950	1463		12	75%
22	100%	100%	1950	1950	16	10	75%

* With idle as the low speed and rated power as the high speed
** With the low and high speeds as defined by the 40CFR86

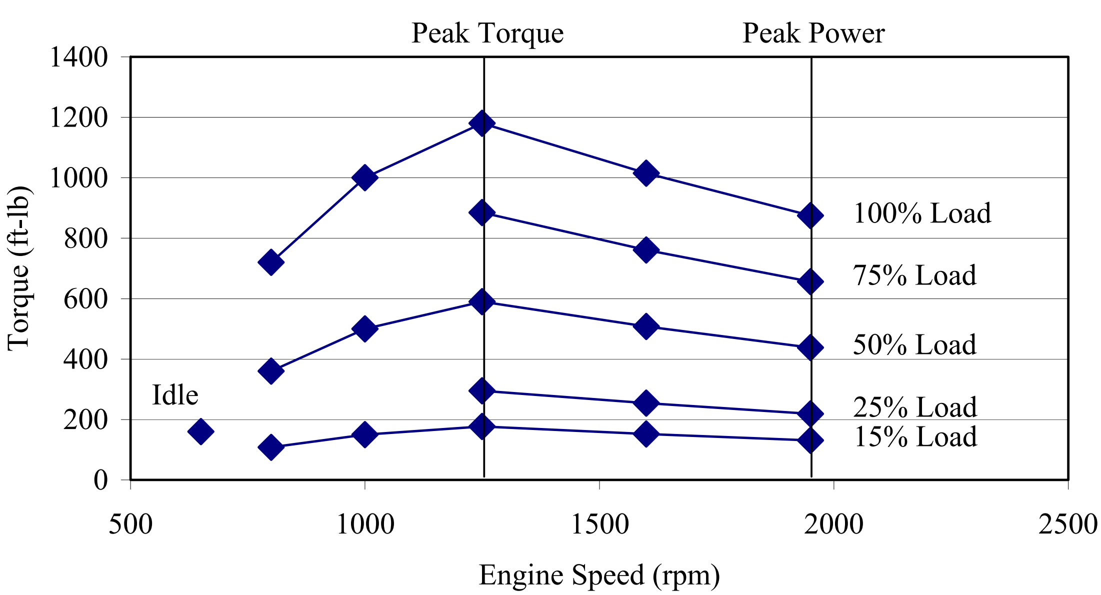

FIGURE 4. STEADY-STATE TEST POINTS

The results of the ignition timing and EGR rate sweeps are shown in Figures 5 through 25. In general, an EGR rate of 5% to 10% gives the highest efficiency at lighter loads, and an EGR rate of 15% gives the highest efficiency at the higher loads. However, an EGR rate of 20% may be more desirable at the higher loads to increase the knock margin and allow the engine to operate at an ignition timing closer to or at maximum brake torque.

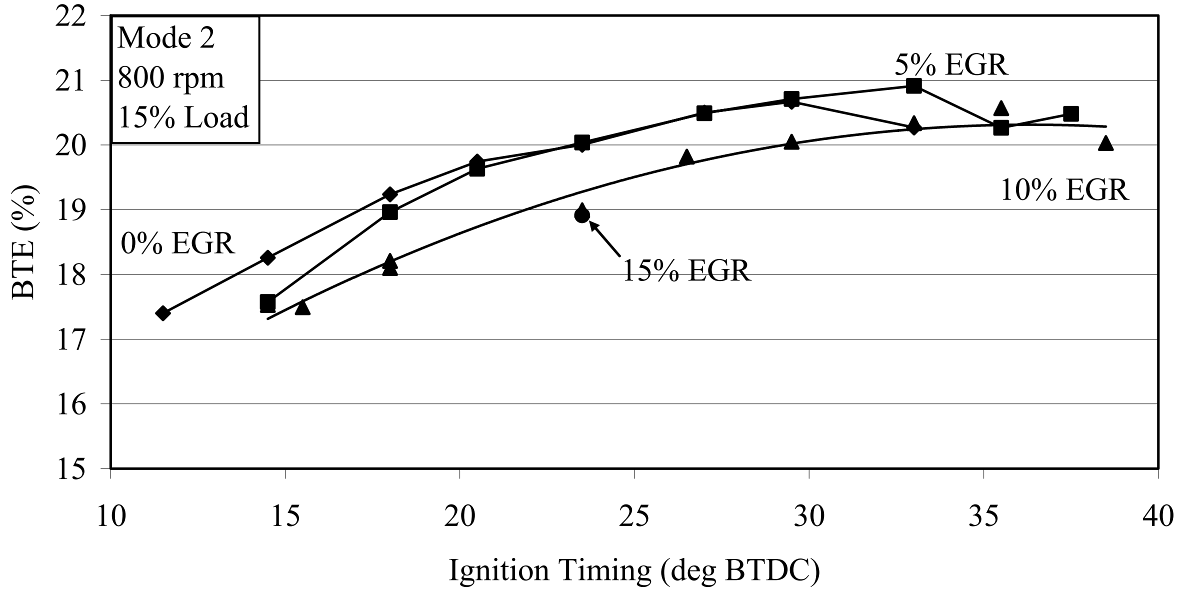

FIGURE 5. IGNITION TIMING AND EGR SWEEPS FOR MODE 2, 800 RPM, 15% LOAD

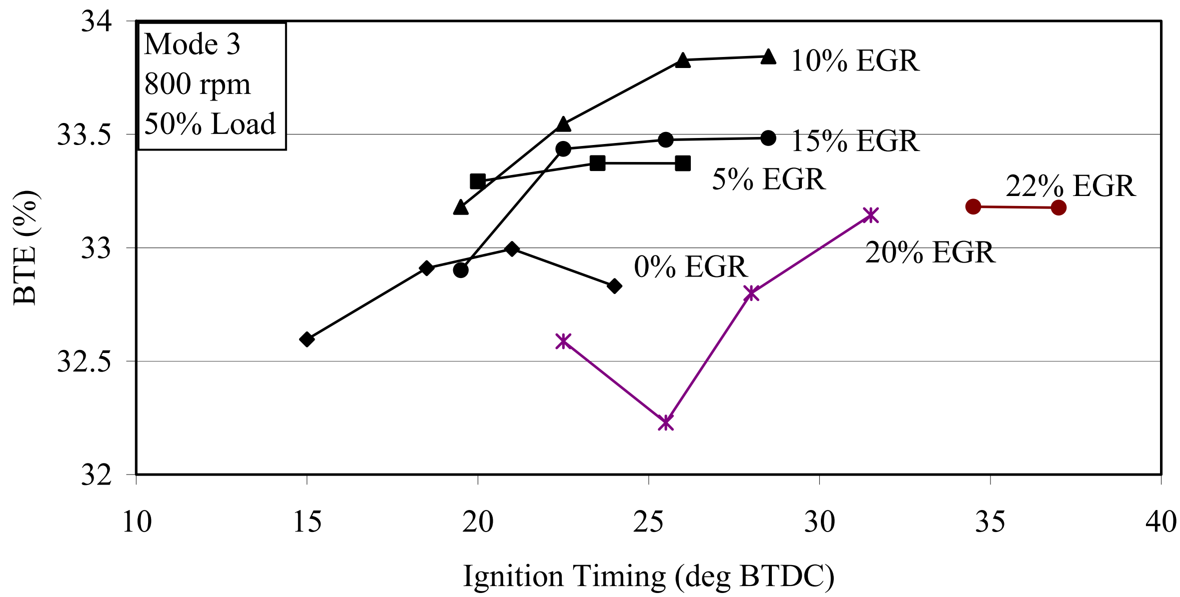

FIGURE 6. IGNITION TIMING AND EGR SWEEPS FOR MODE 3, 800 RPM, 50% LOAD

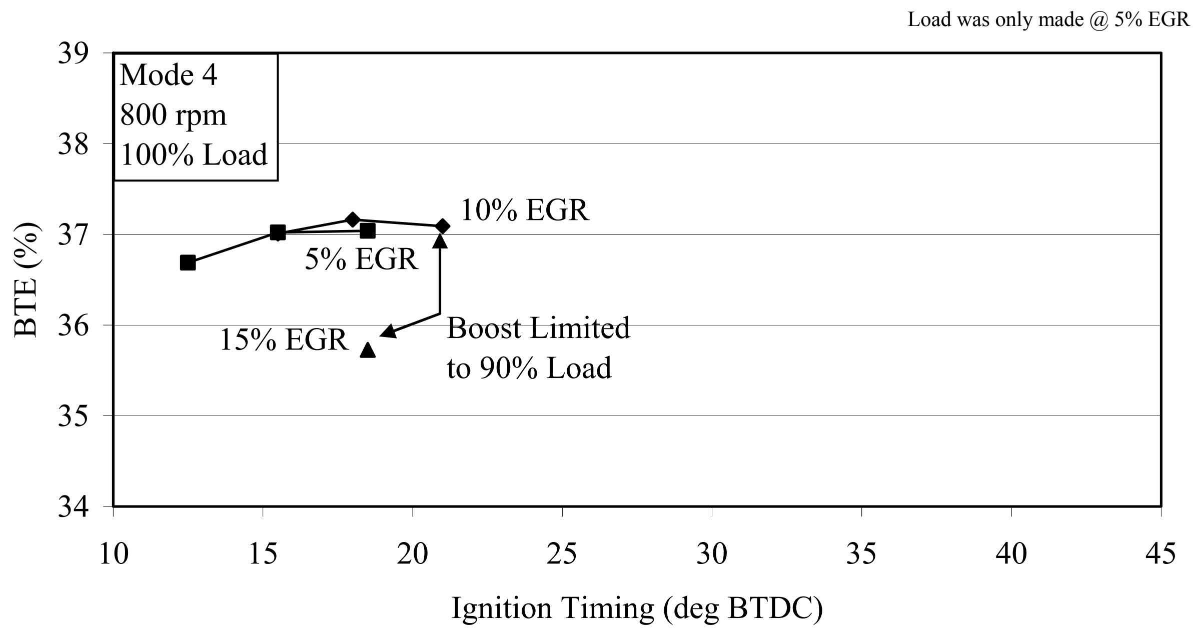

FIGURE 7. IGNITION TIMING AND EGR SWEEPS FOR MODE 4, 800 RPM, 100% LOAD

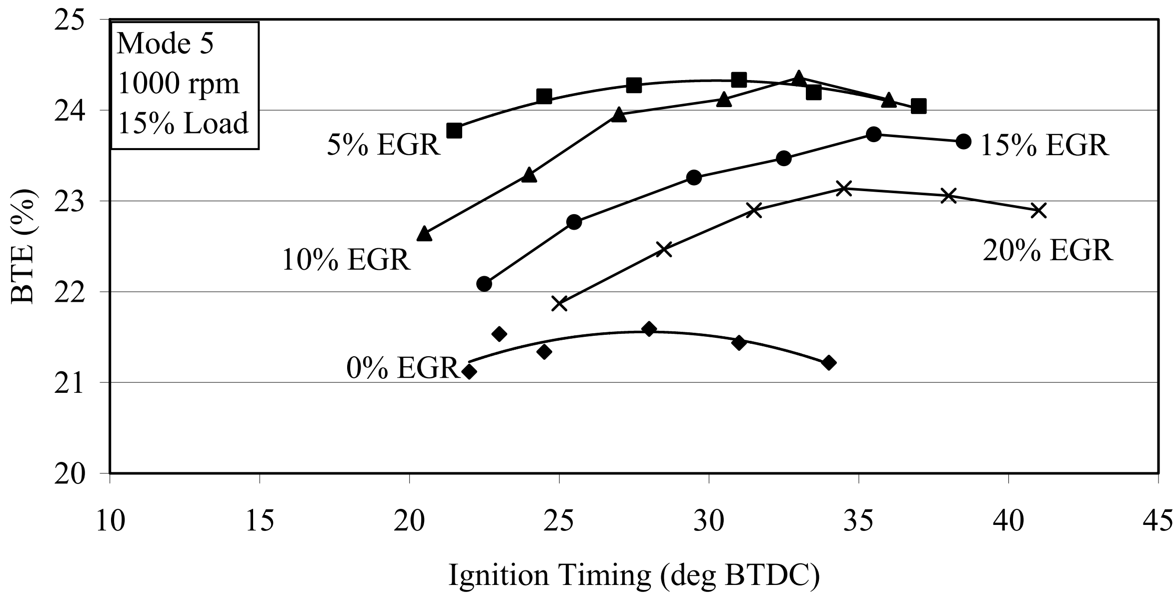

FIGURE 8. IGNITION TIMING AND EGR SWEEPS FOR MODE 5, 1000 RPM, 15% LOAD

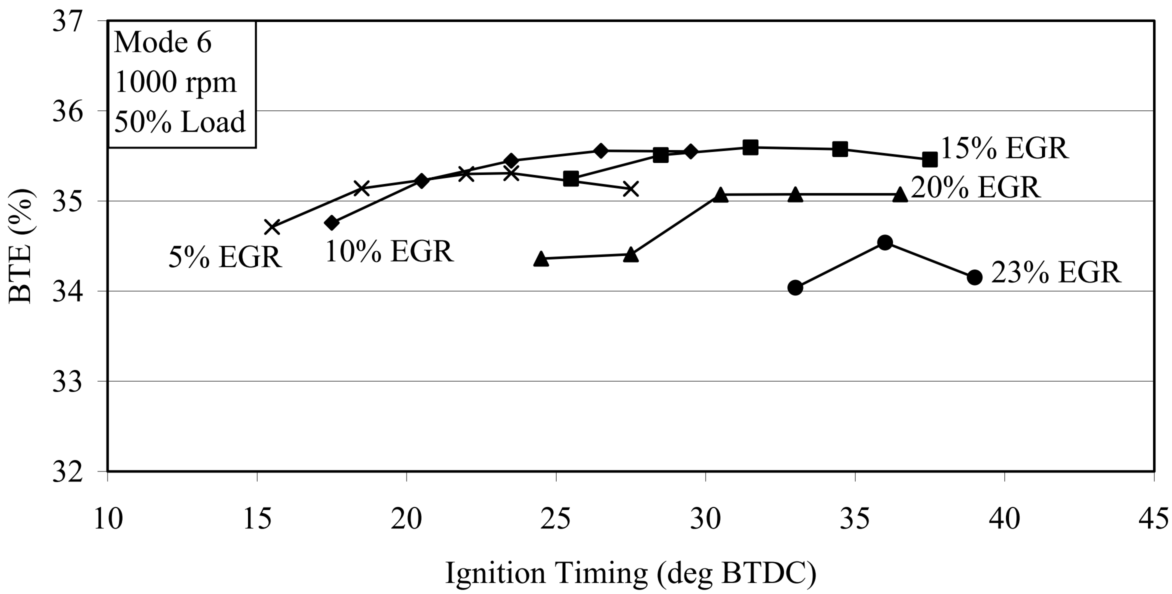

FIGURE 9. IGNITION TIMING AND EGR SWEEPS FOR MODE 6, 1000 RPM, 50% LOAD

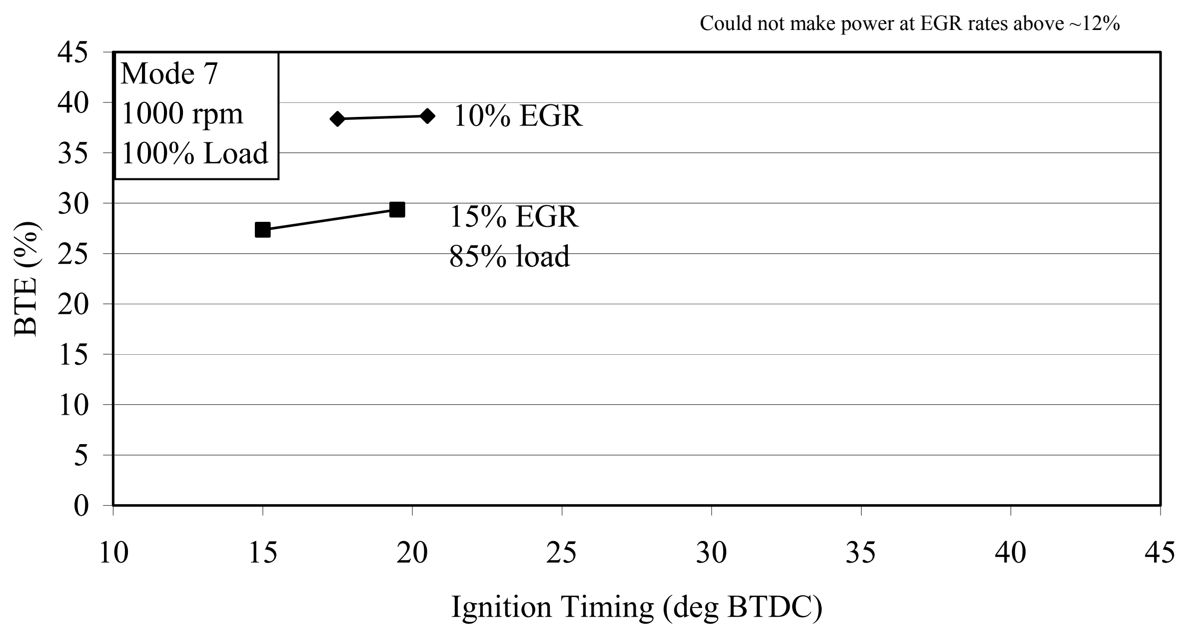

FIGURE 10. IGNITION TIMING AND EGR SWEEPS FOR MODE 7, 1000 RPM, 100% LOAD

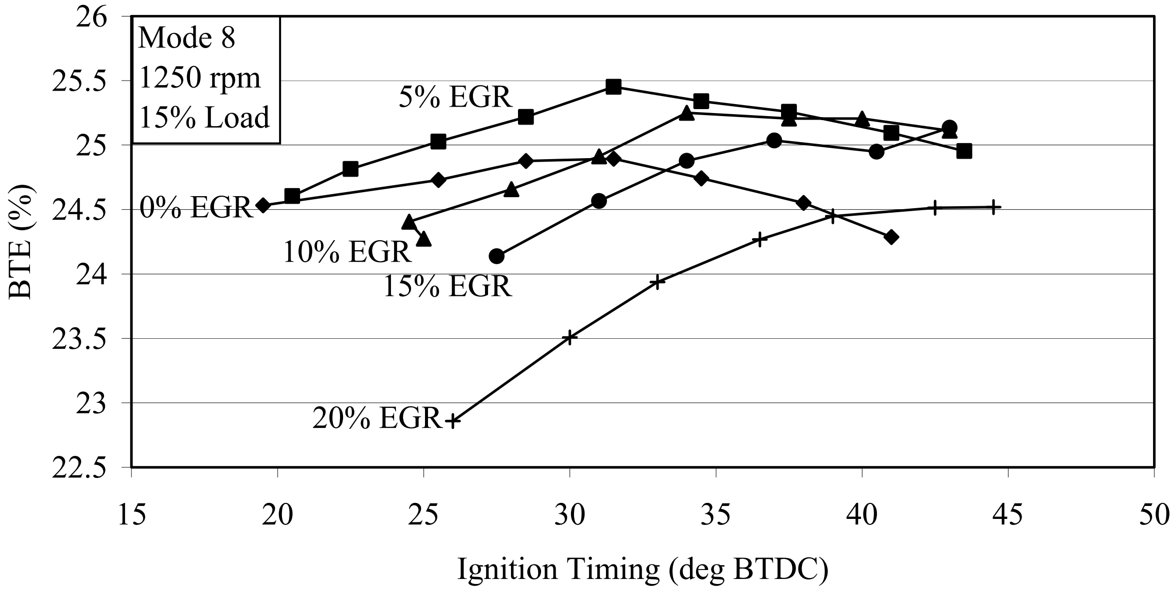

FIGURE 11. IGNITION TIMING AND EGR SWEEPS FOR MODE 8, 1250 RPM, 15% LOAD

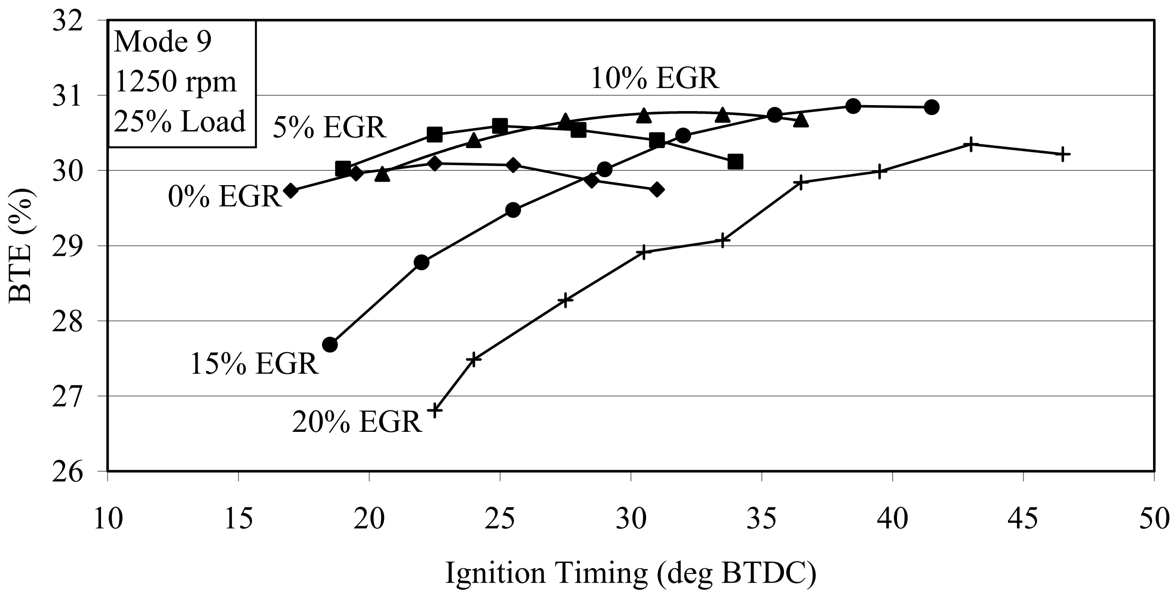

FIGURE 12. IGNITION TIMING AND EGR SWEEPS FOR MODE 9, 1250 RPM, 25% LOAD

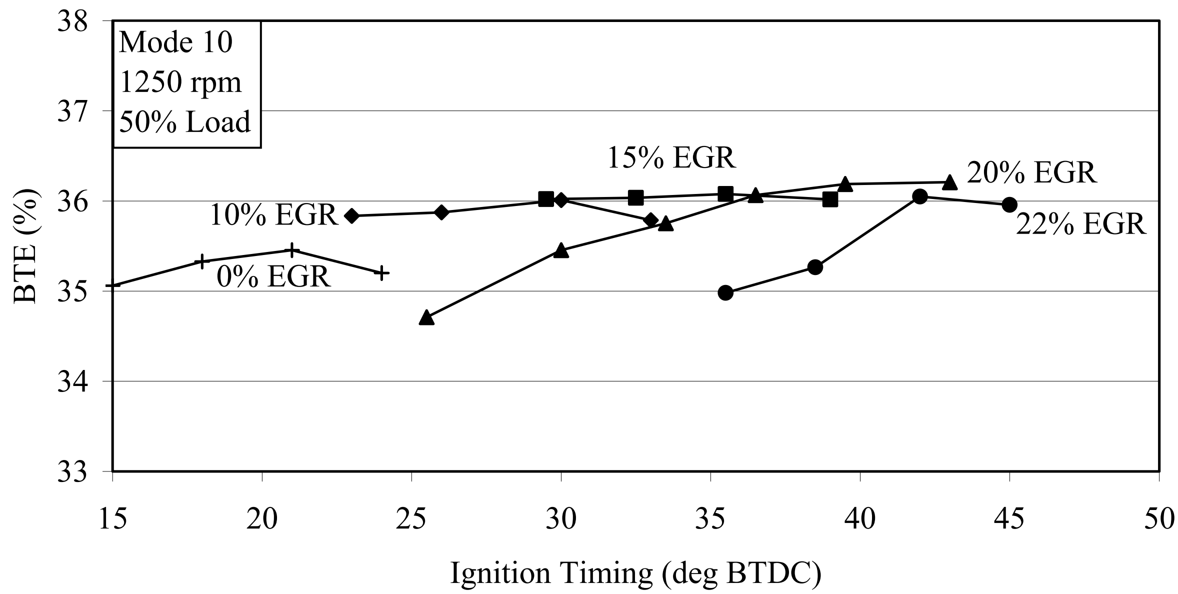

FIGURE 13. IGNITION TIMING AND EGR SWEEPS FOR MODE 10, 1250 RPM, 50% LOAD

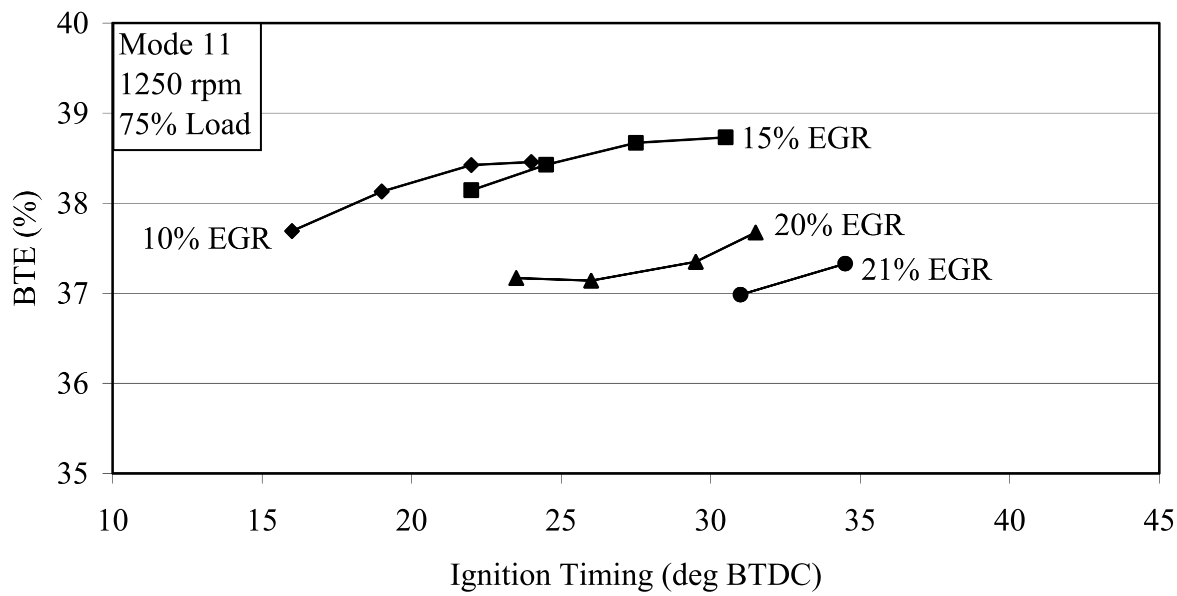

FIGURE 14. IGNITION TIMING AND EGR SWEEPS FOR MODE 11, 1250 RPM, 75% LOAD

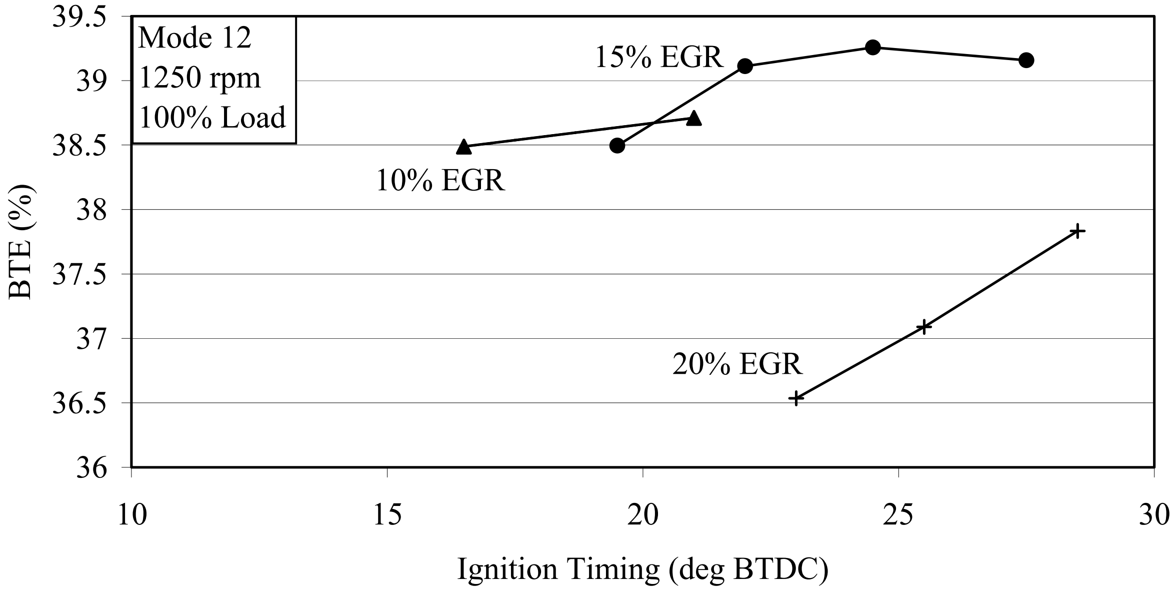

FIGURE 15. IGNITION TIMING AND EGR SWEEPS FOR MODE 12, 1250 RPM, 100% LOAD

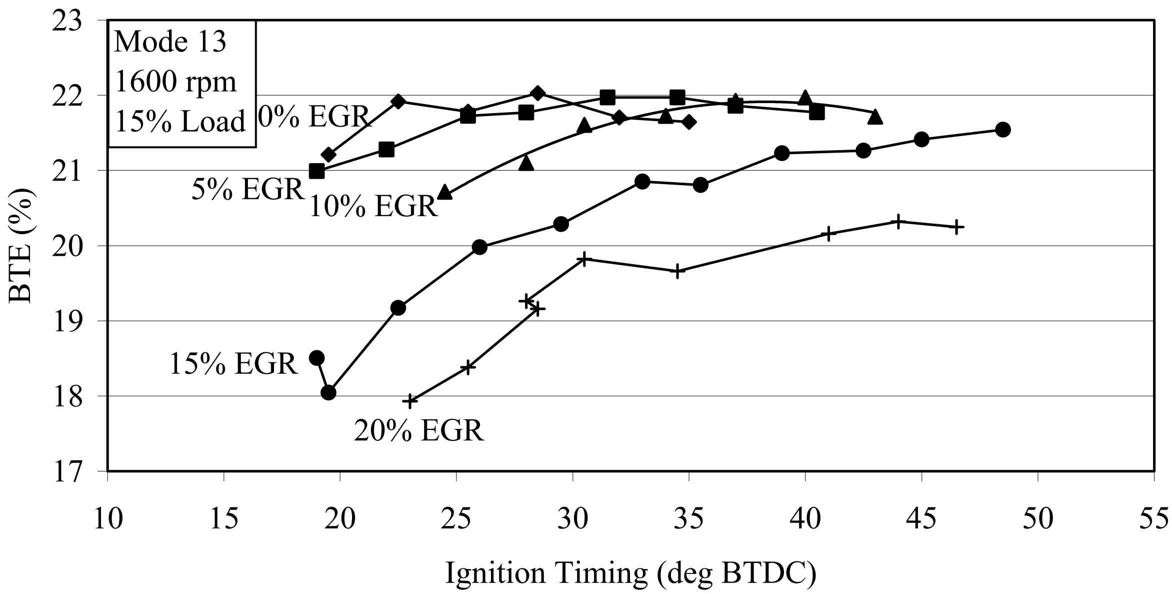

FIGURE 16. IGNITION TIMING AND EGR SWEEPS FOR MODE 13, 1600 RPM, 15% LOAD

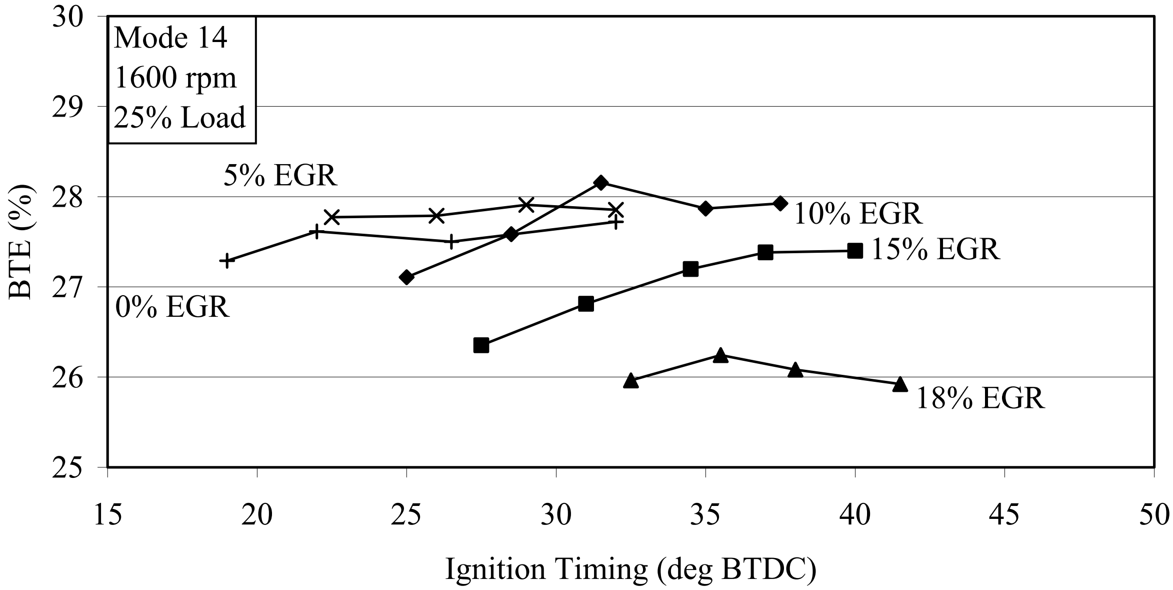

FIGURE 17. IGNITION TIMING AND EGR SWEEPS FOR MODE 14, 1600 RPM, 25% LOAD

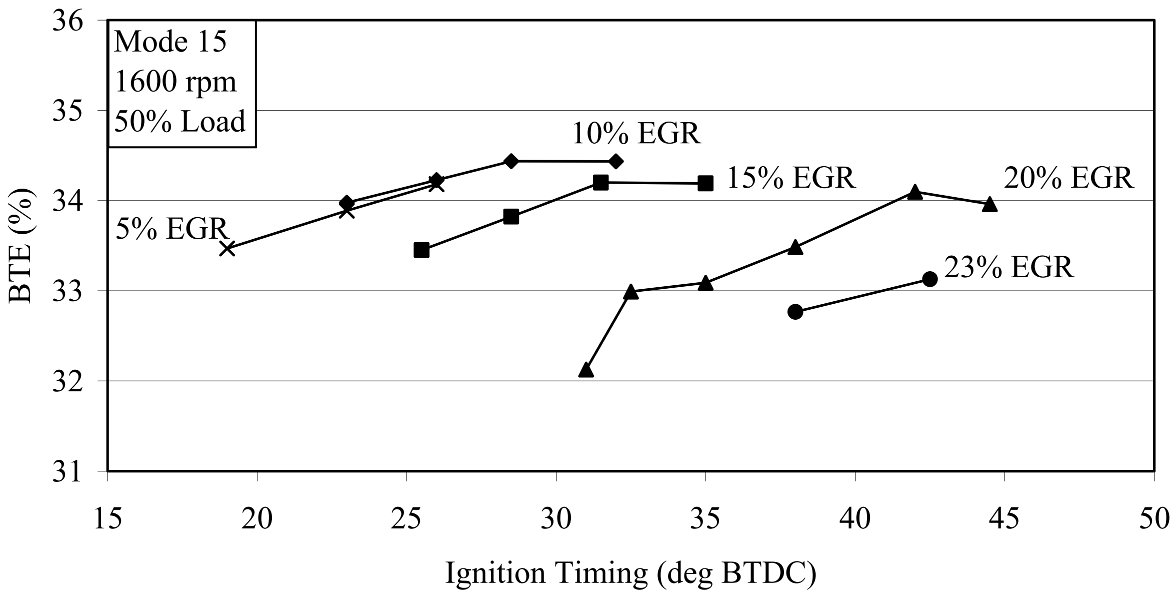

FIGURE 18. IGNITION TIMING AND EGR SWEEPS FOR MODE 15, 1600 RPM, 50% LOAD

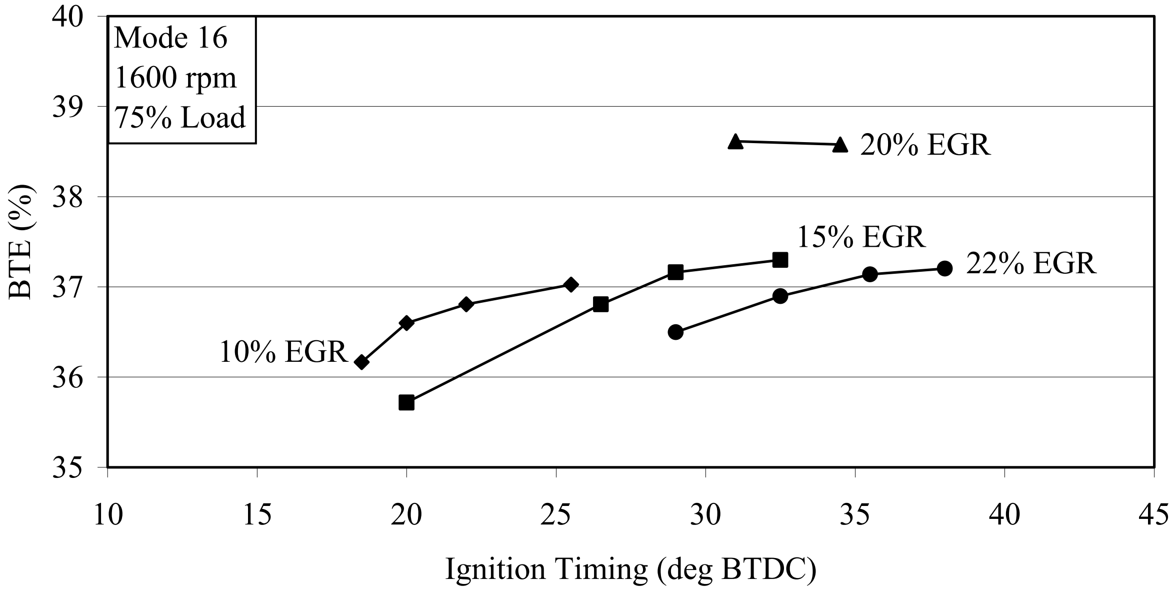

FIGURE 19. IGNITION TIMING AND EGR SWEEPS FOR MODE 16, 1600 RPM, 75% LOAD

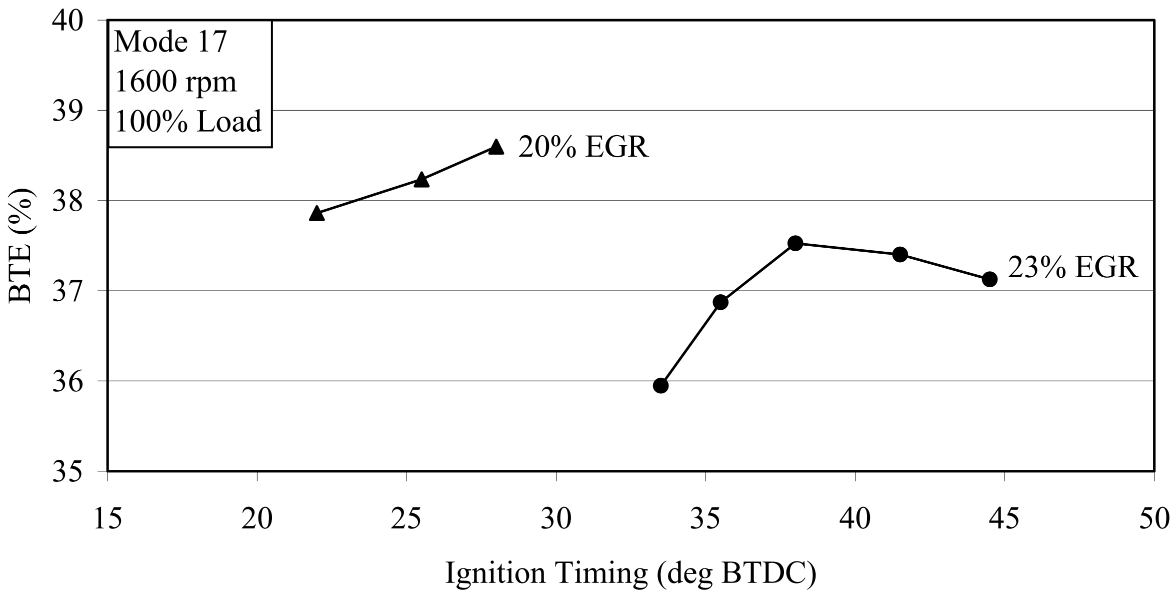

FIGURE 20. IGNITION TIMING AND EGR SWEEPS FOR MODE 17, 1600 RPM, 100% LOAD

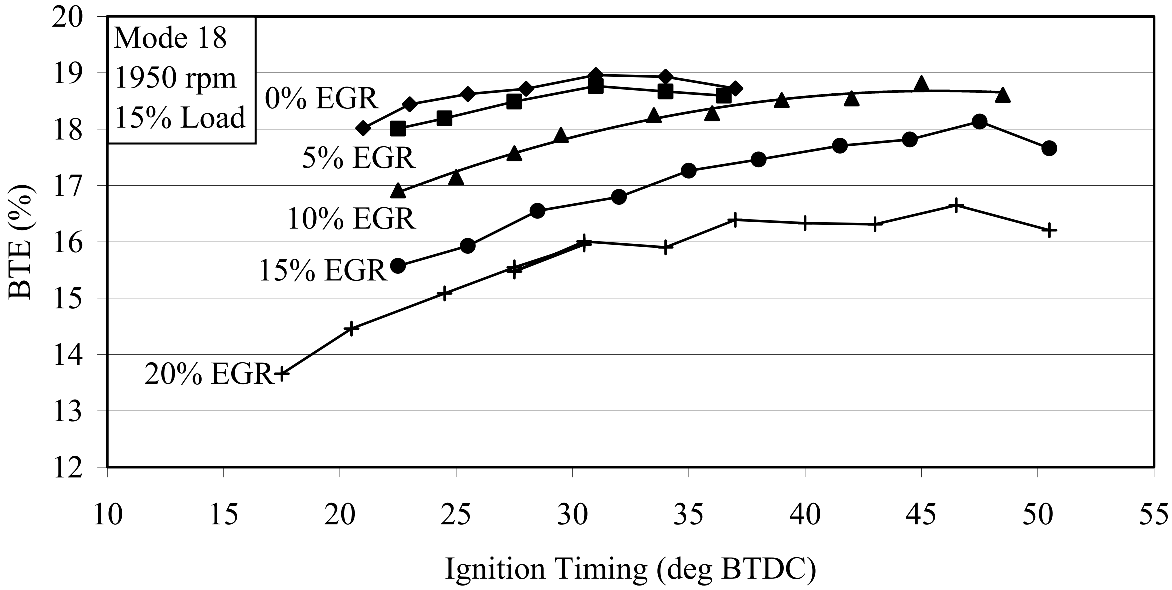

FIGURE 21. IGNITION TIMING AND EGR SWEEPS FOR MODE 18, 1950 RPM, 15% LOAD

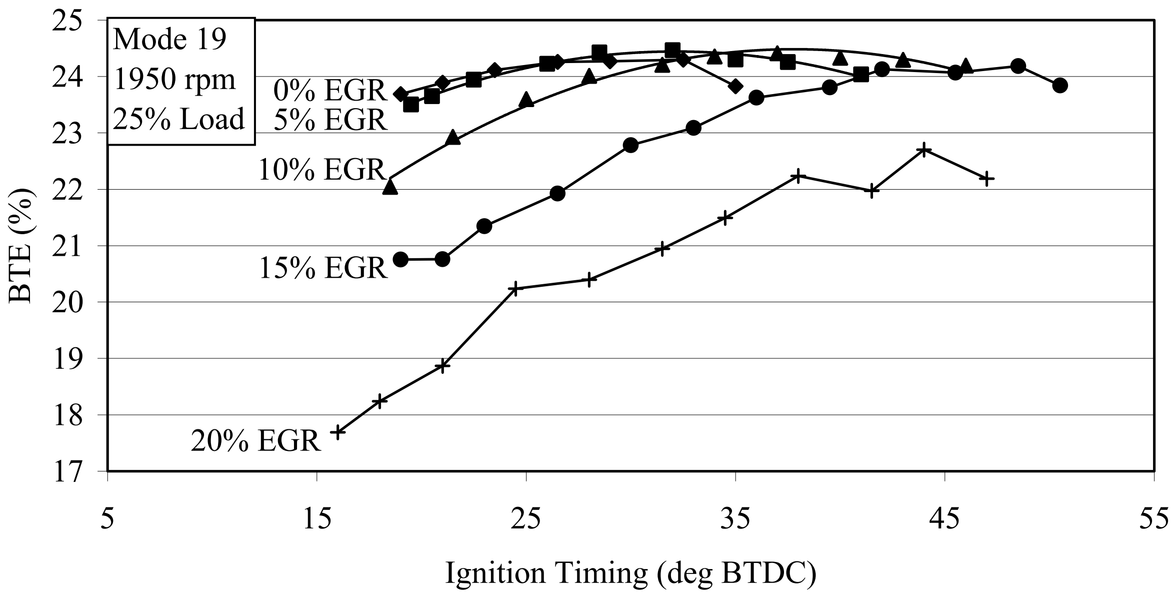

FIGURE 22. IGNITION TIMING AND EGR SWEEPS FOR MODE 19, 1950 RPM, 25% LOAD

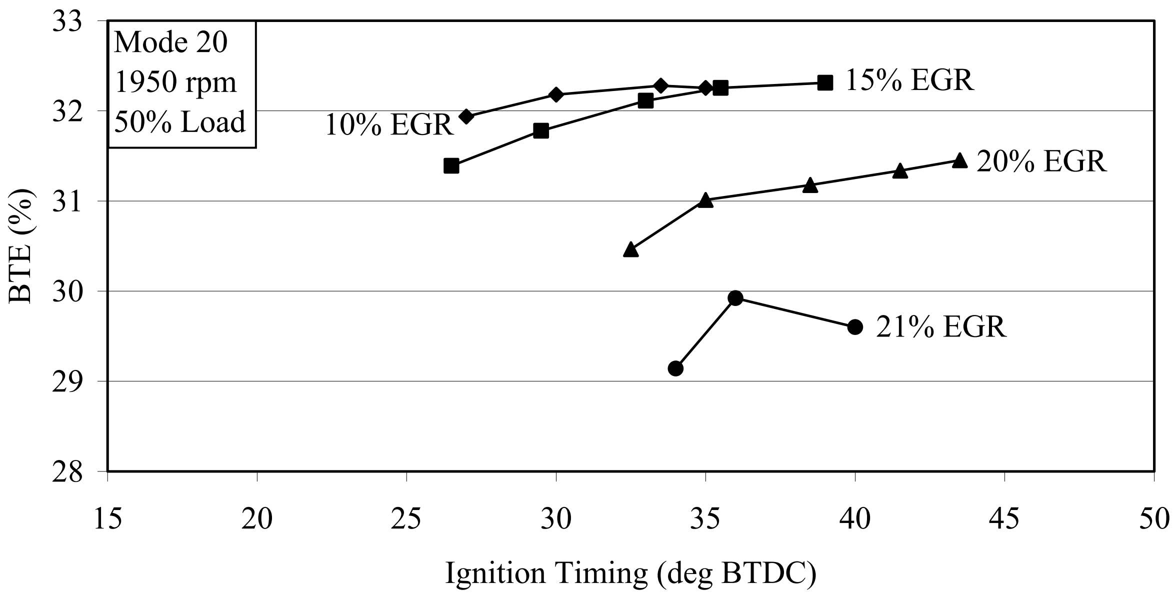

FIGURE 23. IGNITION TIMING AND EGR SWEEPS FOR MODE 20, 1950 RPM, 50% LOAD

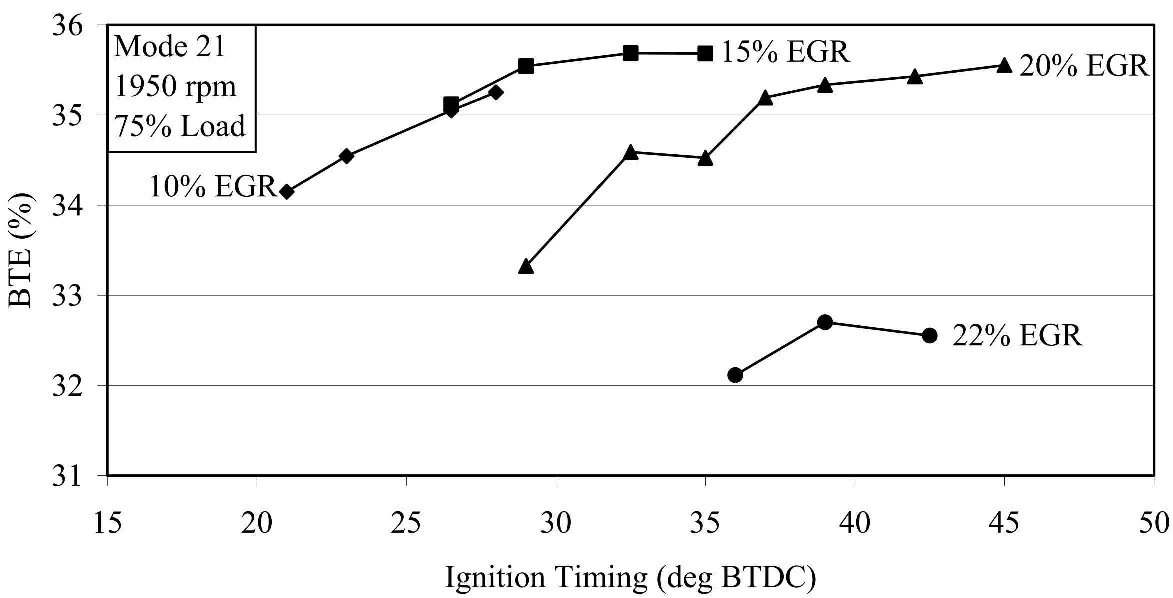

FIGURE 24. IGNITION TIMING AND EGR SWEEPS FOR MODE 21, 1950 RPM, 75% LOAD

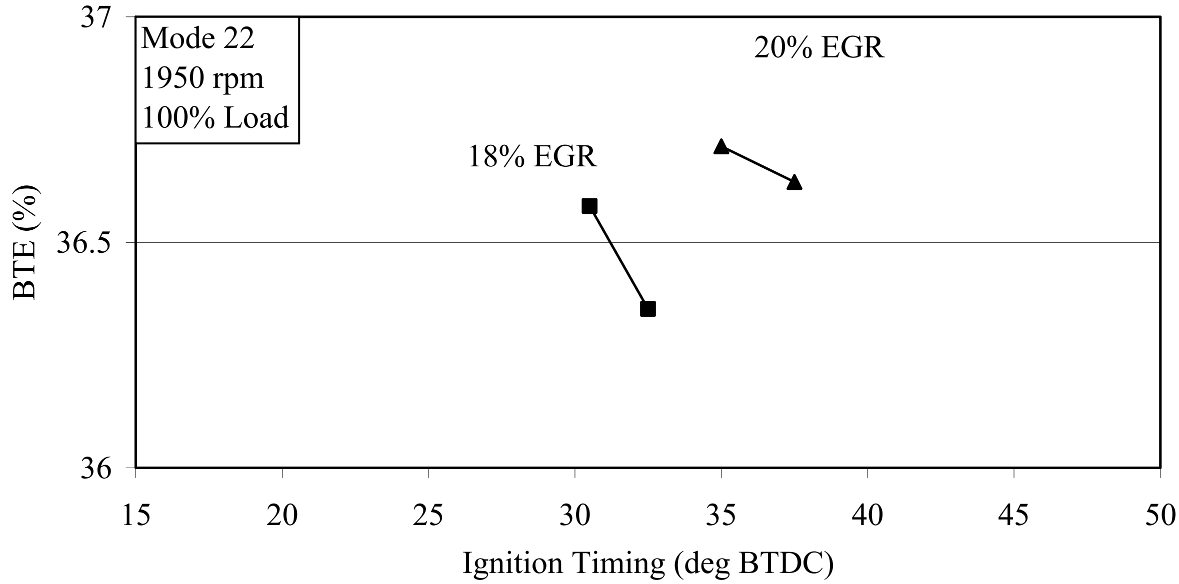

FIGURE 25. IGNITION TIMING AND EGR SWEEPS FOR MODE 22, 1950 RPM, 100% LOAD

2.3 Emissions Testing

To meet the emissions objectives for the project a three-way catalyst was used to reduce the engine out emissions. Two formulations were selected for testing with the 435k mile, 22k hour, 10-year useful life criteria in mind. It should be noted that the durability-testing phase for the three-way catalyst is scheduled to occur in year two of the project. For the engine development phase, the three-way catalyst was de-greened for 125 hours at steady-state conditions. The catalysts selected were “off-the-shelf” formulations available without special order. The off-the-shelf formulations required that two bricks be used to make one catalyst. The bricks were configured so that Pre, Mid, and Post bed emissions could be tested to determine the three-way catalyst’s performance as shown in Figure 26.

The initial testing to obtain zero hour emissions was conducted. The engine had 255.8 development hours at SwRI at the beginning of the emissions testing. There was no catalyst testing performed during the development task.

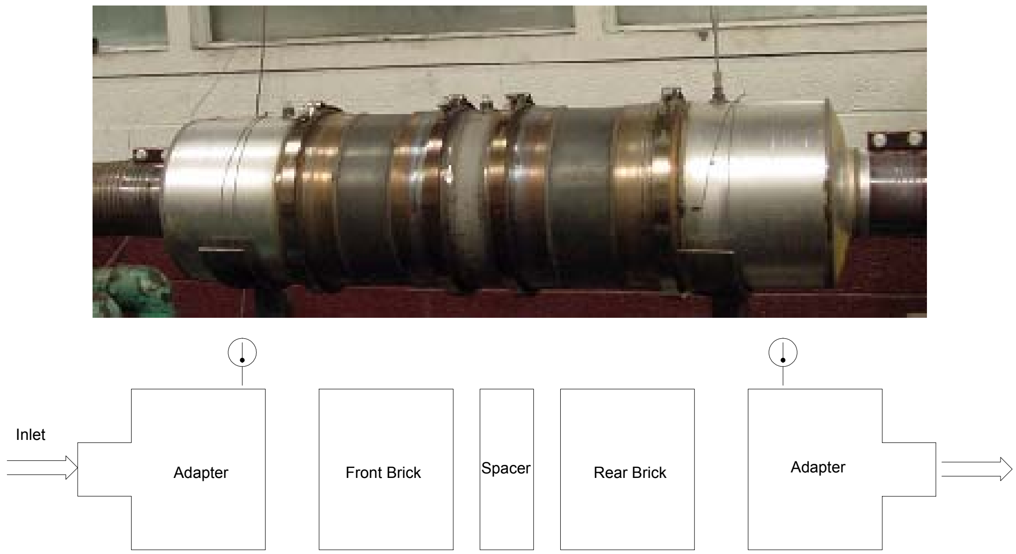

FIGURE 26. COMPLETE THREE-WAY CATALYST USED FOR DEVELOPMENT

The design also incorporates sound attenuation as to eliminate the need for a muffler. Total weight of the catalyst system is approximately 80lbs.

2.3.1 Specifications – Formulations Used

Table 6 outlines the three-way catalyst specifications. Two different formulations were chosen for this application.

TABLE 6: THREE-WAY CATALYST SPECIFICATIONS

Description	Wash Coat	Size / Volume	Total Length
(Cat A) Flow through design Ceramic construction 300 cpsi	Palladium	10.5 x 6 in / (8.5L) Sv = 47000 h-1	44 inches (1.118m)
(Cat B) Flow through design Ceramic construction 300 cpsi	Pt:Pd:Rh	10.5 x 6 in / (8.5L) Sv = 47000 h-1	44 inches (1.118m)

Catalyst (A) is a Pd catalyst. Pd catalysts tend to have a lower light-off temperature and better thermal stability if the catalyst were to be close coupled. All Pd catalysts have been demonstrated to be effective when coupled to light-duty gasoline engines for NOx, CO, and CO_2 reduction [1]. Pd is also desirable because it is more abundant than Pt and thus can help with cost reductions.

The second formulation (B) chosen (Table 6) consisted of Pt:Pd:Rh in case the all Pd formulation could not meet the emissions targets set for the program. Rh favors the reduction catalyst and operates at a richer than stoichiometric mixtures for NO_x reduction (NO_x activity order: Rh>Pt>Pd). Pt is more active for paraffinic HC with molecular size greater than the C_3, which would favor the oxidation of non-methane HC.

Initial testing with the all Pd catalyst had the inlet approximately 72 inches from the turbine outlet. This was considered the worst-case distance that might be installed in a refuse application. However, due to concerns over keeping enough temperature in the catalyst at light loads and during cold start, the three-way catalyst was mounted in the same location as the current muffler location (Figure 27). The three-way catalyst was relocated in the test cell at a distance of 44.8 inches from the turbine outlet and wrapped with exhaust insulation.

FIGURE 27. THREE-WAY CATALYST CHASSIS MOUNT LOCATION

2.3.2 Emissions Testing with Catalyst Formulation A

The first emissions tests were conducted with an all palladium catalyst which is not the most effective catalyst material for reducing NO_x emissions. Transient testing showed the NO_x emissions were approximately 0.5 g/bhp-hr with an equivalence ratio set point of 1.00. The equivalence ratio set point was slowly increased until the NO_x emissions were below 0.2 g/bhp-hr. Table 7 shows the emissions testing results with the catalyst in place. This configuration is below the program targets for NO_x, NMHC, and PM emissions. However, it does not meet the standard for CO emissions. To achieve lower NO_x emissions, the equivalence ratio was set rich of stoichiometric, but operating rich of stoichiometric produces the high CO emissions.

TABLE 7: TRANSIENT EMISSIONS RESULTS WITH CATALYST

Emissions	Cold Start	Hot Start	Composite
THC (g/bhp-hr)	1.713	1.108	1.192
NMHC (g/bhp-hr)	0.000	0.000	0.000
CO (g/bhp-hr)	22.384	23.036	22.945
NO_x (g/bhp-hr)	0.239	0.104	0.123
PM (g/bhp-hr)	0.004	0.003	0.003
CO_2 (g/bhp-hr)	507.6	505.0	505.4
BSFC (lb/bhp-hr)	0.461	0.459	0.459

Transient emissions were also conducted without the catalyst. Table 8 shows the results. NMHC emissions were not determined due to the high level of methane in the exhaust. NMHC emissions are calculated from the total hydrocarbons (THC) and the methane. THC is measured using a flame ionization detector, which is capable of measuring high levels of HC, but methane is measured using a GC, which is not currently capable of the high levels of methane in the exhaust. Therefore, a methane concentration number using the GC was not possible, and the calculated NMHC concentration was not possible. Table 8 also shows the catalyst efficiency for each component. This catalyst has high conversion efficiency for NO_x and THC, but only has 60% efficiency for CO.

TABLE 8: TRANSIENT EMISSIONS RESULTS WITHOUT CATALYST

Emissions	Cold Start	Hot Start	Composite	Catalyst Efficiency
THC (g/bhp-hr)	21.192	15.984	16.679	93
NMHC (g/bhp-hr)	NA	NA	NA	
CO (g/bhp-hr)	57.306	56.850	56.991	60
NO_x (g/bhp-hr)	3.868	3.194	3.284	96
PM (g/bhp-hr)	0.010	0.016	0.015	80
CO_2 (g/bhp-hr)	450.3	421.4	425.2	
BSFC (lb/bhp-hr)	0.505	0.468	0.473	

A 13-mode, steady-state test was also conducted with the catalyst in place. Table 9 shows the results. This configuration is below the target emissions for NO_x, NMHC, and PM. However, it does not meet the target for CO emissions given that the current and future level is 15.5 g/bhp-hr.

TABLE 9: 13-MODE EMISSIONS RESULTS (G/BHP-HR)

Mode	THC	CO	NO_x	PM	CO_2	NMHC	BSFC (lb/bhp-hr)
2	0.241	20.113	0.000		369	0.000	0.338
3	0.060	20.850	0.000		421	0.000	0.382
4	0.200	56.838	0.000		390	0.000	0.364
5	0.000	16.148	0.000		407	0.000	0.365
6	0.183	23.430	0.000		375	0.000	0.348
7	0.019	18.664	0.000		536	0.000	0.477
8	0.066	11.638	0.000		384	0.000	0.339
9	0.007	13.937	0.000		556	0.000	0.487
10	0.089	16.027	0.000		397	0.000	0.356
11	0.010	2.971	0.000		603	0.000	0.512
12	0.108	20.610	0.000		413	0.000	0.375
13	0.036	16.853	0.000		382	0.000	0.344
Comp	0.11	18.72	0.00	0.000	416	0.000	0.375

2.3.3 Emissions Testing with Catalyst Formulation B

Emissions tests were conducted with a palladium/platinum/rhodium catalyst. With this catalyst, the equivalence ratio could be reduced closer to stoichiometric to reduce CO emissions while still maintaining low NO_x emissions. Table 10 shows the results. Emissions were well below the target for the program. Engine certification will require a DF, which will be determined during the remainder of this project. The brake specific fuel consumption (BSFC) of the engine is ~2% higher than the Mack E7G-325 low emissions lean burn engine calibrated to 2.0 g/bhp-hr NO_x. The transient testing showed that almost all of the NO_x emissions are occurring during the first 450 seconds of the Federal Test Procedure (FTP) cycle for both the cold and hot start cycles. Figure 28 and Figure 29 show the NO_x emissions over the cold- and hot-start cycles respectively.

TABLE 10: FTP EMISSIONS RESULTS (G/BHP-HR)

Test	NO_x	THC	NMHC	CO	PM	HCHO (mg/bhp-hr)	BSFC (lb/bhp-hr)
Cold Start	0.203	1.006	0.000	4.757	0.002	1.260	0.444
Hot Start	0.024	0.340	0.000	4.052	0.002	0.061	0.440
Composite FTP	0.049	0.435	0.000	4.153	0.002	0.232	0.441
Hot Start (2nd)	0.020	0.538	0.000	3.750	0.002	0.043	0.442

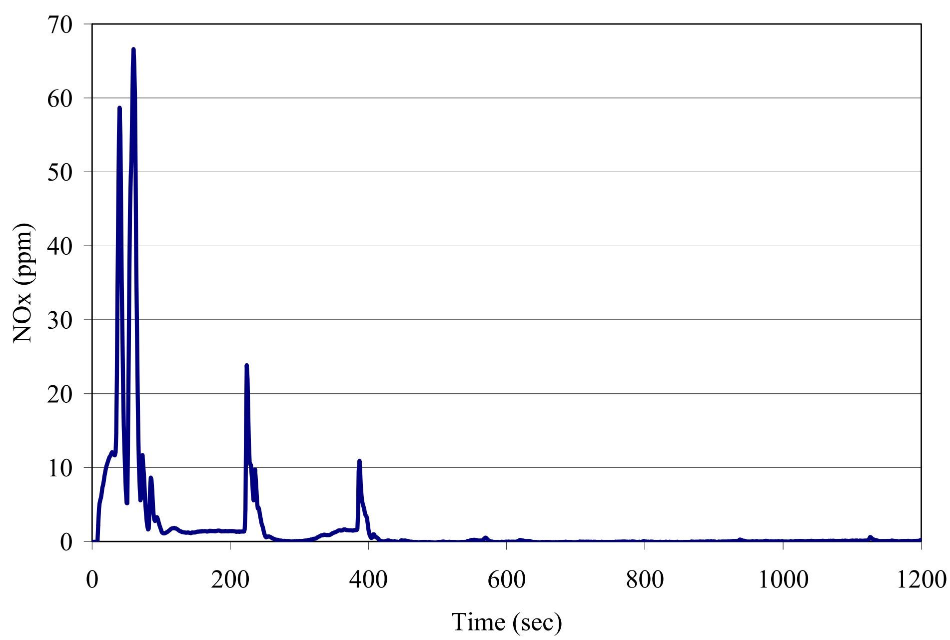

FIGURE 28. NO_X EMISSIONS FROM THE COLD-START CYCLE

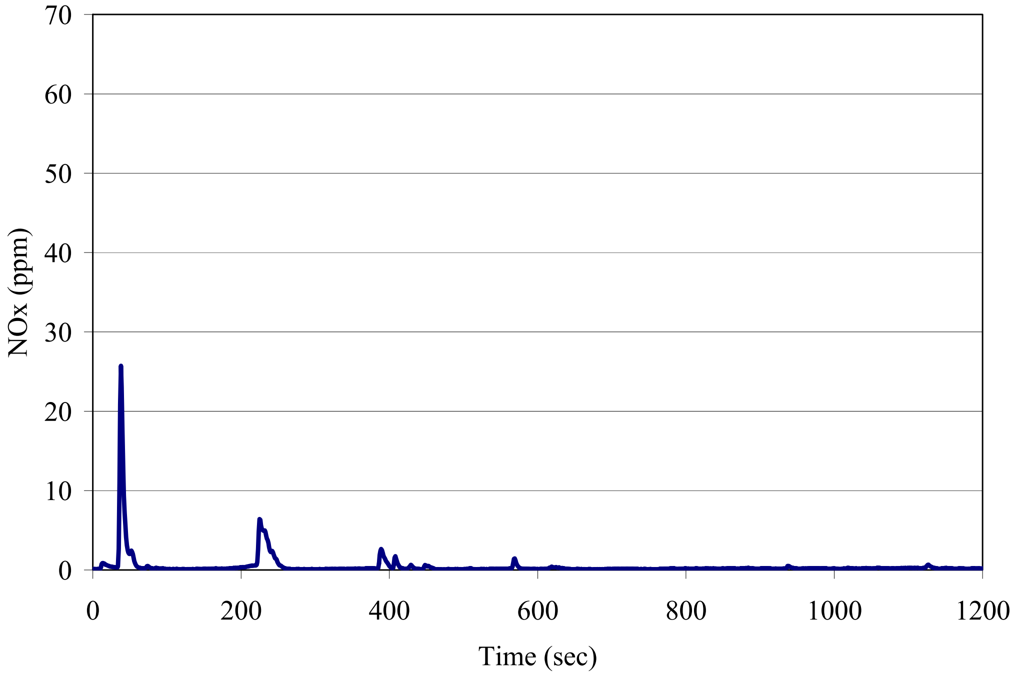

FIGURE 29. NO_X EMISSIONS FROM THE HOT-START CYCLE

A hot-start transient emissions test was also conducted without the catalyst. Table 11 shows the results. NMHC emissions were not possible due to the high level of methane in the exhaust. NMHC emissions are calculated from the THC and the methane. THC is measured using a flame ionization detector, which is capable of measuring high levels of HC, but methane in measured using a GC, which is not currently capable of the high levels of methane in the exhaust. Therefore, a methane concentration number using the GC was not possible, and the calculated NMHC concentration was not possible. Table 11 also shows the catalyst efficiency for each component. This catalyst has high conversion efficiency for NO_x and THC, and has 88% efficiency for CO.

TABLE 11: TRANSIENT EMISSIONS RESULTS WITHOUT CATALYST

Emissions	**Hot Start (no catalyst)**	**Hot Start (with catalyst)**	**Catalyst Efficiency**
THC (g/bhp-hr)	9.451	0.340	96
NMHC (g/bhp-hr)	NA		
CO (g/bhp-hr)	33.519	4.052	88
NO_x (g/bhp-hr)	3.749	0.024	99
PM (g/bhp-hr)	0.016	0.002	88
CO_2 (g/bhp-hr)	439.3	514.7	
BSFC (lb/bhp-hr)	0.437	0.440	

Table 12 shows results from the 13-mode test. Again, engine emissions were below the program targets for both the composite number and the modes in the not-to-exceed (NTE) area.

TABLE 12: 13-MODE EMISSIONS RESULTS (G/BHP-HR)

Mode	THC	CO	NO_x	PM	CO_2	NMHC	BSFC (lb/bhp-hr)
1	0.002	4.479	0.297		699.3	0.000	0.594
2	0.004	1.493	0.020		392.3	0.000	0.333
3	0.000	2.490	0.036		444.3	0.000	0.378
4	0.003	1.913	0.023		409.4	0.000	0.347
5	0.000	2.858	0.056		435.3	0.000	0.371
6	0.000	1.221	0.037		402.9	0.000	0.341
7	0.000	1.197	0.108		533.3	0.000	0.451
8	0.021	1.798	0.023		365.9	0.000	0.311
9	0.000	0.907	0.109		540.5	0.000	0.457
10	0.054	2.171	0.028		401.0	0.000	0.341
11	0.000	0.786	0.112		596.1	0.000	0.504
12	0.054	1.905	0.040		425.1	0.000	0.361
13	0.028	3.847	0.061		473.3	0.000	0.404
Comp	0.020	2.000	0.040	0.000	430.0	0.000	0.365

Table 13 shows the composition of the fuel used for the FTP and 13-mode testing.

TABLE 13: FUEL COMPOSITION FOR EMISSIONS TESTING

Component	EPA Spec	CARB Spec	FTP	ESC
Methane	89.0 (min)	90.0 ± 1.0	90.518	90.446
Ethane	4.5 (max)	4.0 ± 0.5	4.107	4.082
C_3 and higher HC content	2.3 (max)	2.0 ± 0.3	1.991	2.029
C_6 and higher HC content		0.2 (max)	0.004	0.006
Hydrogen		0.1 (max)	0.000	0.000
Carbon Monoxide		0.1 (max)	0.000	0.000
Oxygen		0.5 (max)	0.000	0.000
Inert Gas (sum of CO_2 and N_2)	4.0 (max)	3.5 ± 0.5	3.380	3.437

3. PROTOTYPE ENGINES

3.1 Introduction

The project also requires that two refuse trucks be fitted with the E7GT engine and placed in service within the south coast of California for six months during the second year of the project. Waste Management is supplying the refuse haulers for the demonstration and will operate the trucks from one of its south coast terminals. The trucks will operate over a normal collection route for a six-month demonstration period not yet identified. Two Mack E7G engines were modified to accept the EGR system, VGT turbo, and advanced cooling system.

Prototype engine development was done in parallel with the control and combustion system development. The component modification was identified based on the packaging constraints of the chassis. The hardware necessary for the control system was determined from the engine development and the EGR flow requirements for the engine. The parts for the prototype engines were borrowed from the Mack ASET® (Application Specific Engine Technology) diesel product line, which helped reduce the engineering time to verify initial component durability. The necessary components were successfully fabricated and installed to form the two demonstration engines. Component modification and fabrication will be verified during the scheduled 1500-hour durability test within year two of the project.

3.1.1 Demonstration engine design

The engines were based on the current Mack E7G lean burn engine calibrated at 2.0 g/bhp-hr NO_x + NMHC. The EGR system was borrowed from the Mack diesel ASET® cooled EGR (AC) engine currently in production. The components were adapted to the E7GT to be installed in the Mack refuse (MR) chassis. However, Mack does not currently install the AC engine into the MR chassis, so a custom exhaust manifold had to be fabricated to allow the addition of the Holset VG turbocharger and to fit within the packaging constraints of the MR chassis. The following parts were borrowed from the ASET® AC diesel engine:

- Water pump
- Thermostat housing
- Water manifold
- EGR valve
- EGR cooler
- VGT controller
- Crankshaft pulley
- Inlet manifold [borrowed from the Application Specific Emissions Technology – Internal Exhaust Gas Recirculation (AI) diesel].

The components were integrated onto the Mack E7G to form the E7GT.

3.2 Component Modifications

3.2.1 Intake manifold

Because of the cooled EGR water pump and water manifold configuration, the intake manifold from the AI diesel product had to be used and modified to accept the Woodward Flo-Tech™ throttle control. The new mounting location was done by reducing the original air entrance height by 4 inches (Figure 30) and attaching a rectangular mounting pad for the Flotec throttle control. This would allow the fuel-mixing ring to retain the same installation height as the Mack E7G.

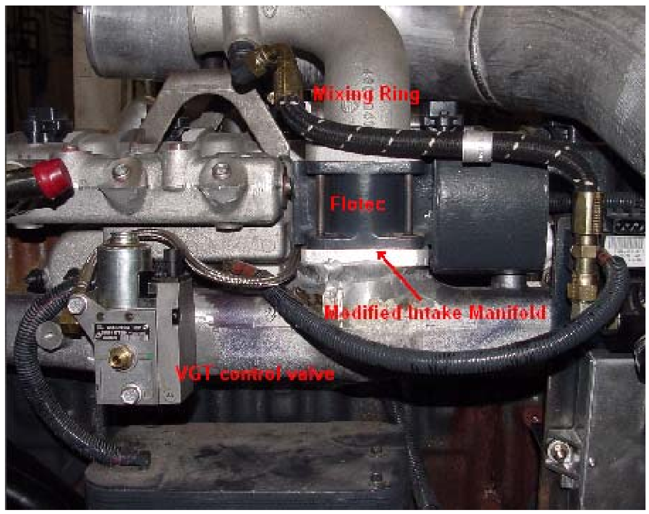

FIGURE 30. MODIFIED INTAKE MANIFOLD

A mounting pad was also added to the intake manifold to accept the VGT control valve. Since the manifold was borrowed from the AI diesel product, a location existed where the engine control unit (ECU) would be mounted. This same location was used to mount the Woodward powertrain control module (PCM) HD, fuel metering valve (FMV), manifold absolute pressure (MAP), and pre-throttle pressure (PtHP) sensors. A custom mount was designed and fabricated that would fit the same mounting points as the diesel ECU (Figure 31).

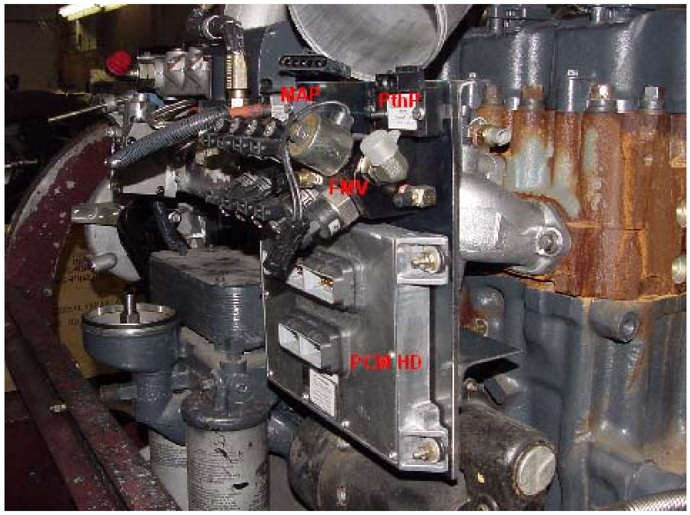

FIGURE 31. PCM, FMV, MAP AND PTHP MOUNTING

3.2.2 Cooled EGR system

The EGR system was adapted to the Mack E7G by adding the Lisk EGR hydraulic control valve and the EGR cooler from the Mack AC diesel engine. The E7G uses the Mack PLN block that does not have the required mounting location for the EGR cooler. A custom mounting bracket was fabricated to fasten the cooler to the block in the same location as the E7 AC. The cooler retained the same installed dimensions as the ASET® version to ensure that the connections to the cooler would be compatible with the ASET® water pump system (Figure 32).

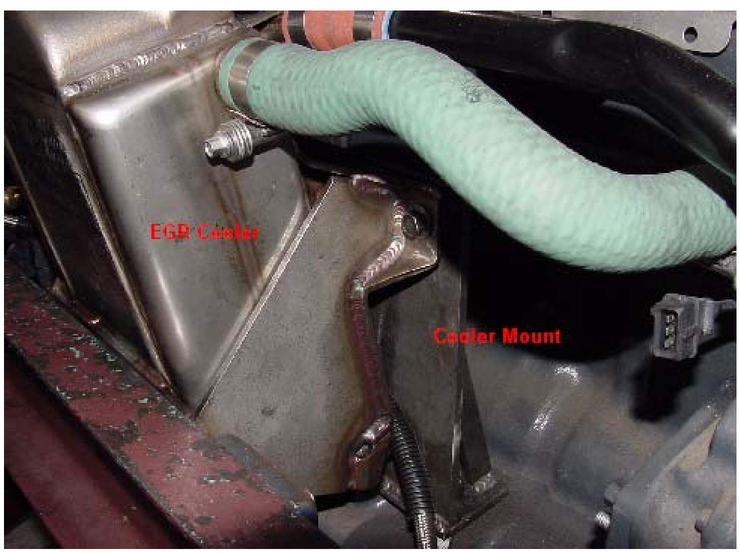

FIGURE 32. EGR COOLER AND MOUNTING BRACKET

Figure 33 shows the water pump system used for all current ASET® engines produced by Mack. The system would provide the correct coolant flows through the EGR cooler for exhaust gas cooling.

FIGURE 33. ASET® COOLANT PUMP SYSTEM

3.2.3 EGR Valve

The E7GT used the Lisk EGR valve, which is controlled with engine oil pressure, and the electronic control solenoid also borrowed from the Mack ASET® diesel family. The valve is mounted to the hot side of the EGR cooler, which helps prevent contaminants from building up on the valve. Typically the Lisk valve mounts directly to the exhaust manifold and requires a specific mounting surface never designed for the MR chassis. The MR chassis requires a 45-degree turbo mount to fit within the constraints of the cab width. The Lisk valve was mounted directly to the inlet of the EGR cooler to save space and enable the use of the current Mack E7G exhaust manifold center section.

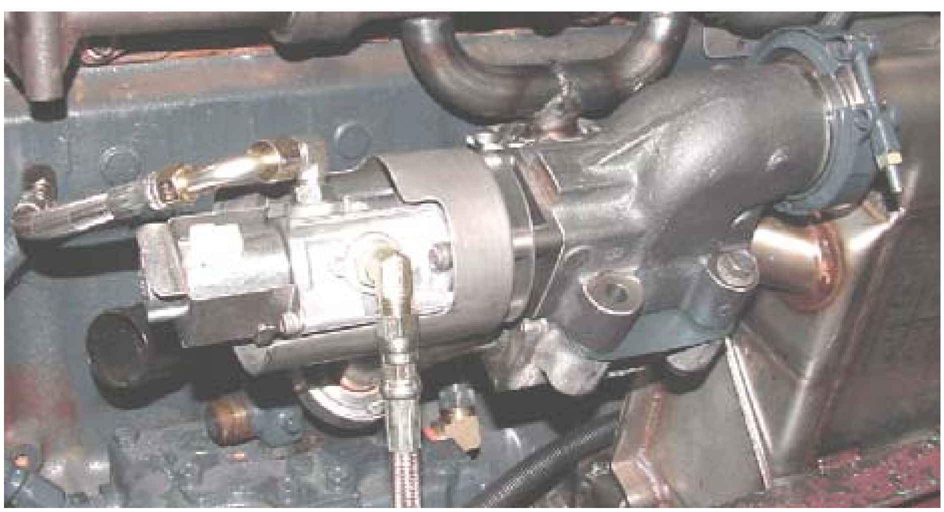

FIGURE 34. LISK VALVE MOUNTED TO EGR COOLER

4.0 HEAT REJECTION

The addition of cooled EGR results in more heat energy rejected to the engines cooling system. Heat rejection testing was done to determine if the cooling system currently used for the Mack E7G natural gas engine would have the ability to reject the extra heat energy from the EGR cooler and still maintain the proper engine coolant temperature. The testing indicated that 25% more heat energy would be rejected to the engine coolant due to the addition of the EGR cooler. Given the additional cooling requirements, auxiliary cooling in the form of an additional fan and radiator will need to be added to reject an additional 3000-4000 Btu/hr.

5.0 RESULTS AND CONCLUSIONS

The conclusions of the project to date are summarized below.

- A stoichiometric natural gas fueled engine with EGR was successfully developed.
  - This engine was developed using the lean burn Mack E7G natural gas fueled engine as the basis.
  - A Woodward OH2 engine controller was adapted to this engine.
  - An EGR system was added to the engine along with algorithms to control the EGR and maintain proper air-fuel ratio control with varying EGR rates.
  - Ignition timing and EGR rate sweeps were conducted.

- The initial non-deteriorated results for this engine were below the program targets for all regulated emissions.
  - NO_x emissions are 0.049 g/bhp-hr, which is less than one-fourth of the 2010 standard.
  - Particulate emissions are 0.002 g/bhp-hr, which is one-fifth of the 2010 standard.

- Integration of the engine into the refuse hauler chassis was completed.
  - Components were modified and/or fabricated as needed to integrate the Woodward OH2.0 engine control system into the engine.
  - Components were modified and/or fabricated as needed to integrate the EGR system into the engine.

6.0 REFERENCE

1. Hepburn, J.; Patel, K.; Meneghel, M.; Gandhi, H. “Development of Pd-Only Three-Way Catalyst Technology.” Society of Automotive Engineers, 1994. Document number: 941058.

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14. ABSTRACT *(Maximum 200 Words)*
This report discusses the development of a E7G 12-liter, lean-burn natural gas engine—using stoichiometric combustion, cooled exhaust gas recirculation, and three-way catalyst technologies—for refuse haulers.

15. SUBJECT TERMS
heavy-duty natural gas engines; stoichiometric combustion; cooled exhaust gas recirculation; three-way catalyst

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