Demonstration of a Low-NO\textsubscript{x} Heavy-Duty Natural Gas Engine

PROJECT IMPACT
This project demonstrated a heavy-duty natural gas engine emission reduction strategy resulting in oxides of nitrogen (NO\textsubscript{x}) emissions of 0.54 g/bhp-h and particulate matter (PM) emissions of 0.004 g/bhp-h. Reducing NO\textsubscript{x} and PM emissions is crucial for meeting increasingly strict regulations (Figure 1). By 2010, the U.S. Environmental Protection Agency (EPA) will require NO\textsubscript{x} emissions of 0.2 g/bhp-h or less and PM emissions of 0.01 g/bhp-h or less. The technology demonstrated in this project may help natural gas engines meet the 2010 requirements. It is anticipated that this would lead to more extensive use of natural gas vehicles, resulting in reduced petroleum consumption.

DUAL-FUEL ENGINES
The project was led by DOE's National Renewable Energy Laboratory (NREL) and Clean Air Power (formerly Clean Air Partners). Clean Air Power, in partnership with Caterpillar, Inc., has developed Dual-Fuel\textsuperscript{TM} natural gas engine technology. The Dual-Fuel system converts standard Caterpillar diesel engines to run primarily on natural gas; a small amount of diesel fuel consumed along with the natural gas enables compression ignition. In this project, a Caterpillar C-12 Dual-Fuel engine (410 hp/1,250 ft-lb) was equipped with improved combustion and aftertreatment strategies.

EMISSION REDUCTION STRATEGIES
Two emission reduction strategies were proposed. Passive clean and cold exhaust gas recirculation (PACCOLD-EGR), which combines diesel particulate filter (DPF) and EGR technologies, was expected to reduce NO\textsubscript{x} emissions to 0.5 g/bhp-h. Active clean and cold (ACCOLD) EGR, which combines the PACCOLD-EGR system with a lean-NO\textsubscript{x} catalyst, was expected to reduce NO\textsubscript{x} emissions further, to 0.2 g/bhp-h. Use of a catalyzed DPF was expected to reduce PM emissions to below 0.01 g/bhp-h. During the project, it was concluded that the proposed ACCOLD-EGR system could not meet the project objectives, and this strategy was abandoned.

PACCOLD-EGR
In an EGR system, part of the exhaust gas is reintroduced into the intake air and induced back into the engine. The recirculated exhaust gases absorb some of the energy released during combustion of the fuel. This decreases peak combustion temperature, the most critical factor favoring high NO\textsubscript{x} formation. The EGR fraction also displaces oxygen, making less available for combustion, thus reducing the probability of interaction between nitrogen and oxygen even under lean conditions.

The PACCOLD-EGR system uses a full-time DPF in the exhaust, which greatly simplifies the EGR system because cooled EGR can be injected directly into the turbo compressor inlet. This is possible because the exhaust gas has been filtered and is...
clean enough to enter the compressor and aftercooler without risk of contamination. The Clean Air Power PACCOLD-EGR system (Figure 2) consists of an Engelhard DPX™ catalyzed DPF, EGR cooler and Venturi assembly (both designed and fabricated by Clean Air Power), and EGR filter.

ENGINE TESTING

Engine tests were designed to evaluate the effect of PACCOLD-EGR in conjunction with existing control variables and strategies used on current C-12 Dual-Fuel engines. A baseline engine and one with the PACCOLD-EGR system were tested over the 13-mode European Stationary Cycle (ESC). Several factors were manipulated to optimize emissions and fuel economy: EGR rate, gas lambda (excess air ratio), pilot injection timing, EGR temperature, and air charge temperature.

RESULTS AND CONCLUSIONS

The following average emissions and fuel consumption were demonstrated with the PACCOLD-EGR system over the ESC:

- Nonmethane hydrocarbons (NMHC) .... 1.44 g/bhp-h
- Carbon monoxide (CO) ............ 0.05 g/bhp-h
- NOx ........................................... 0.54 g/bhp-h
- PM ............................................ 0.0037 g/bhp-h
- Brake-specific energy consumption (BSEC) ........ 7,610 Btu/bhp-h

Figure 3 compares emissions and energy consumption from engines with and without the PACCOLD-EGR system.

The project resulted in the following conclusions:

- The C-12 Dual-Fuel engine equipped with the PACCOLD-EGR system demonstrated 0.54 g/bhp-h NOx and 0.004 g/bhp-h PM.
- The PACCOLD-EGR system is based on fully validated aftertreatment components available today (the California Air Resources Board has verified the Clean Air Power catalyzed DPF for use with some Dual-Fuel engines).
- A reduction in NOx of about 4% for 1% of EGR mass fraction is suggested as a working guideline.
- EGR mass fraction and pilot injection timing are the dominant parameters affecting NOx emissions.
- Unfavorable tradeoff of hydrocarbons for NOx is evident with retarded pilot injection timing.

Successful implementation of the PACCOLD-EGR technology will rely on the integration into a commercial package of catalyzed DPF and EGR components.

RELATED PUBLICATIONS AND WEB SITES

The report Next Generation Natural Gas Vehicle Program Phase I: Clean Air Partners 0.5 g/hp-h NOx Engine Concept is available from the Alternative Fuels Data Center at www.afdc.doe.gov. Hard copies are available from the Alternative Fuels Hotline at 1-800-423-1363 or hotline@afdc.nrel.gov. The Next Generation Natural Gas Vehicle activity is part of DOE’s Natural Gas Vehicle Technology Forum. For more information, visit www.ott.doe.gov/ngvtf.