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**ETSD**

# CRADA Final Report
# For
# CRADA Number NFE-08-01415

# Materials-Enabled
# High-Efficiency (MEHE)
# Heavy-Duty Diesel Engines

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**CRADA Final Report (ORNL-Caterpillar, 2011)**
**CRADA Agreement Number NFE-08-01415**

# Materials-Enabled High-Efficiency (MEHE) Heavy-Duty Diesel Engines

**A Final Report submitted to the**
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## Abstract

The purpose of this Cooperative Research and Development Agreement (CRADA) between UT-Battelle, Inc. and Caterpillar, Inc. was to improve diesel engine efficiency by incorporating advanced materials to enable higher combustion pressures and temperatures necessary for improved combustion. The project scope also included novel materials for use in advanced components and designs associated with waste-heat recovery and other concepts for improved thermal efficiency. Caterpillar initially provided ORNL with a 2004 Tier 2 C15 ACERT™ diesel engine (designed for on-highway use) and two 600 hp motoring dynamometers.

The first year of the CRADA effort was focused on establishing a heavy-duty experimental engine research cell. First year activities included procuring, installing and commissioning the cell infrastructure. Infrastructure components consisted of intake air handling system, water tower, exhaust handling system, and cell air conditioning. Other necessary infrastructure items included the fuel delivery system and bottled gas handling to support the analytical instrumentation. The second year of the CRADA focused on commissioning the dynamometer system to enable engine experimentation. In addition to the requirements associated with the dynamometer controller, the electrical system needed a power factor correction system to maintain continuity with the electrical grid. During the second year the engine was instrumented and baseline operated to confirm performance and commission the dynamometer. The engine performance was mapped and modeled according to requirements provided by Caterpillar. This activity was further supported by a Work-for-Others project from Caterpillar to evaluate a proprietary modeling system. A second Work-for-Others activity was performed to evaluate a novel turbocharger design. This project was highly successful and may lead to new turbocharger designs for Caterpillar heavy-duty diesel engines. During the third (and final) year of the CRADA, a novel valve material was evaluated to assess high temperature performance and durability. A series of prototype valves, composed of a unique nickel-alloy was placed in the engine head. The engine was aggressively operated using a transient test cycle for 200 hours. The valve recession was periodically measured to determine valve performance. Upon completion of the test the valves were removed and returned to Caterpillar for additional assessment.

Industrial in-kind support was available throughout the project period. Review of the status and research results were carried out on a regular basis (meetings and telecons) which included direction for future work activities. A significant portion of the industrial support was in the form of information exchange and technical consultation.

## 1. Statement of Objectives

The following goals were pursued in this project:

1. Improve thermal and combustion efficiency by incorporating new materials as in-cylinder components and assess engine response to novel material and component applications
2. Identify pathways to improving efficiency through the utilization of advanced materials
3. Characterize selected component and materials performance
4. Identify potential thermal exhaust management approaches

## 2. Benefits to the Funding DOE Office's Mission

This collaboration between ORNL and Caterpillar, Inc. was established to take advantage of advances in new materials technologies and demonstrate significant improvements in engine efficiency for heavy-duty diesel engines. The project directly addressed important barriers such as more extreme combustion environments, long lead times for materials commercialization, and the need to reduce engine mass and cost.

The diesel engine is considered the most fuel efficient powertrain. However, to reduce dependence on foreign oil, further efficiency improvements are desired for on-highway use. Reducing the United States dependence on foreign oil is a top priority of the DOE Office of Energy Efficiency and Renewable Energy.

## 3. Technical Discussion of Work Performed by All Parties

As the first step in this collaborative effort, Caterpillar provided ORNL with two General Electric motoring dynamometers and a 2004 C15 ACERT™ diesel engine to support experimental testing in a new engine test cell at the National Transportation Research Center (NTRC). The engine and one dynamometer were installed as part of the initial commissioning of Cell 7 at the NTRC in the first year of this CRADA. Later improvements to the test cell completed under the CRADA include installation of a harmonic filtering system to eliminate electrical power factor problems in the building when the DC dynamometer operates under heavy load and the addition of acoustic insulation to reduce noise levels both in the control room and elsewhere in the building.

ORNL researchers gathered baseline performance data to compare with data provided by Caterpillar and to use in thermodynamic analysis of the engine and validation of modeling results. This baseline testing also supported an associated WFO project with Caterpillar, where second-law thermodynamic analysis of the output of Caterpillar's proprietary engine modeling software was performed. This second-law analysis gives additional information about how much available energy (a.k.a. exergy) is present in various exhaust and coolant flows, which will enable more informed decisions to be made regarding prioritizing the eliminating of losses as well as where waste heat recovery and similar systems could be most effectively implemented. Another later WFO project with Caterpillar involved successful testing of an experimental turbocharger with novel geometry that enabled significant improvements in engine efficiency at realistic drive-cycle operating conditions. These experiments were conducted using the new test cell that was commissioned as a part of this CRADA.

One significant material testing campaign was performed under this CRADA. First, Caterpillar supplied ORNL with a set of exhaust valves made from a new nickel-based alloy designed for improved durability at high temperatures. The valves were installed in the C15 ACERT™ engine, and the engine was operated on a transient test cycle specified by Caterpillar for 200 hours.

Valve lash was measured for the initial untested condition and periodically during the course of the 200 hour test period. The lash results are shown in Table 1 and do not indicate a significant difference in the valve recession for those composed of the nickel-based alloy compared to the standard valves. The valves were removed from the engine for further evaluation by personnel at Caterpillar, Inc. Throughout the experimental run, the engine performance and efficiency was

noted. The results showed no decrease in performance with the new alloys.

**Table 1—Valve Lash Measurements**

| Cylinder # | Exhaust Valve Material | Valve # | 0 hours | 30 hours | 50 hours | 77 hours | 200 hours |
|---|---|---|---|---|---|---|---|
| 1 | Ni Alloy | 1 | 0.030 | 0.028 | 0.028 | 0.028 | 0.028 |
| | | 3 | 0.030 | 0.028 | 0.028 | 0.028 | 0.028 |
| 2 | Standard | 5 | 0.030 | 0.028 | 0.028 | 0.028 | 0.028 |
| | | 7 | 0.030 | 0.028 | 0.028 | 0.028 | 0.028 |
| 3 | Ni Alloy | 9 | 0.030 | 0.028 | 0.028 | 0.028 | 0.028 |
| | | 11 | 0.030 | 0.028 | 0.028 | 0.028 | 0.028 |
| 4 | Standard | 13 | 0.030 | 0.028 | 0.027 | 0.027 | 0.027 |
| | | 15 | 0.030 | 0.028 | 0.027 | 0.027 | 0.027 |
| 5 | Ni Alloy | 17 | 0.030 | 0.029 | 0.028 | 0.028 | 0.028 |
| | | 19 | 0.030 | 0.028 | 0.028 | 0.028 | 0.028 |
| 6 | Standard | 21 | 0.030 | 0.028 | 0.027 | 0.027 | 0.027 |
| | | 23 | 0.030 | 0.028 | 0.027 | 0.027 | 0.027 |

## 4. Subject Inventions

No inventions were filed under this CRADA.

## 5. Commercialization Possibilities

The materials tested at ORNL in the course of this CRADA can be implemented by Caterpillar, if the added cost is considered to be justified from a business perspective.

## 6. Plans for Future Collaboration

Due to Caterpillar's exit from the on-highway market and DOE's present lack of an off-highway mandate, this CRADA is being discontinued. Informal collaborations and/or WFO agreements between Caterpillar and ORNL may continue separate from DOE funding.

## 7. Conclusions

A unique experimental facility was established at ORNL to evaluate material contributions to energy efficiency for heavy-duty diesel engines. This facility was constructed from the ground up over a 2-year period into a fully-functioning engine research cell. During this period, two Work-for-Other activities were completed successfully and plans were laid out for work on novel

valve and manifold materials. During the third year of the CRADA a nickel-alloy valve was evaluated. The engine performance was unchanged with the new valves and the valves performed successfully throughout the 200 hour test period. The valves have been removed for subsequent metallurgical evaluation by Caterpillar.