The Engines & Energy Conversion Laboratory
Department of Mechanical Engineering
Colorado State University

Colorado State University
Knowledge to Go Places

August 2006

Technical Capabilities and Research Directions: Natural Gas Reciprocating Engines

Background: Engines & Energy Conversion Laboratory

The Engines & Energy Conversion Laboratory (EECL) is a unique research / education program housed in the Department of Mechanical Engineering. The laboratory was established in the Old Fort Collins Power Plant in June 1992. In the ensuing 14 years the laboratory has grown to become one of the largest and most influential engines research programs in the United States. The EECL is widely recognized as an international leader in the fields of large gas engines for power generation and compression, small 2-stroke cycle engines for use in developing countries, alternative fuels for automobiles, computational fluid dynamic (CFD) modeling of engines, and optical combustion diagnostics. The Department has invested in the laboratory through the recent hires of two new faculty members, who have established new EECL programs in diesel engines, laser diagnostics, and plasma applications in engines.

Probably the most understated value of the EECL is its students. Since inception the EECL has populated industry with engineers who make an impact. Students from the EECL gain hands on experience with large natural gas engines that is unavailable in other Mechanical Engineering programs.

Areas of Expertise

Air Pollution Formation and Control

The EECL specializes in the study of emissions formation in internal combustion engines. The lab has particular expertise in emissions from large stationary engines, small two-stroke engines, and engines operating on alternative fuels. The laboratory has developed emissions control technologies for all of these applications.

The EECL conducts its research in several ways:

- Basic science studies of chemical kinetics, combustion, and pollution formation
- Advanced computation, using computational fluid dynamics, to examine mixture formation and predict emissions from internal combustion engines; engine simulations to investigate air flow phenomena, engine performance trends, and component design
- Advanced optical diagnostics to study air/fuel mixing, combustion, and emissions formation. The EECL houses the world's largest optical engine, complete with a wide variety of sophisticated laser diagnostics.
- Engine testing. The EECL has the most extensive engine testing capabilities of any university in North America, with capabilities for testing engines of over 150,000 pounds and producing over 2500 horsepower.

Emission measurement capabilities include:

- 5-gas emissions analysis: chemiluminescence measurement of NOx, flame ionization detection of hydrocarbons, paramagnetic detection of oxygen, non-dispersive infrared detection of CO and CO_2
- Fourier Transform Infrared Analysis: speciated measurement of HC through C4, speciated measurement of NOx compounds (NO, NO_2, N_2O, N_2O_5, NH_3, etc), Sox compounds, aldehydes (formaldehyde, acetaldehyde, acrolein). New capabilities are being added to allow measurement of BTEX compounds.
- Gas Chromatograph analysis: primarily for fuel, but also for exhaust hydrocarbon speciation
- Cavity Ringdown Spectroscopy: capable of measuring ultra-low concentrations

Toxic Air Contaminants

Toxic contaminants / hazardous air pollutants (HAPs) are a class of mutagenic and carcinogenic pollutants which have not been regulated prior to 2004. The EPA lists 189 HAPs compounds produced by combustion sources. The HAPs compounds which are potentially produced by engines in significant quantities include formaldehyde, acetaldehyde, acrolein, the BTEX compounds (benzene, toluene, xylene, ethylbenzene), and 1,3,butadiene. Measurement of HAPs can be difficult, and the EECL was the first group to document and systematically study HAPs formation from natural gas engines. EECL researchers have made recent contributions in the following areas:

- Measurement - Advanced the state-of-the-art for measuring HAPs, including the development of specialized Fourier transform infrared (FTIR) spectrometry-based techniques and collaborating with other researchers on GC-MS (gas chromatograph – mass spectrometer) and liquid-phase measurements.
- Experimental Studies - Documented high emissions of formaldehyde (one of the 189 HAPs compounds) from natural gas engines.
- Analytical / Chemical Kinetic Modeling - Developed theories (now widely accepted) to describe the formation of formaldehyde in natural gas engines.
- Mitigation - Developed techniques to reduce / prevent formaldehyde formation.
- Legislative Support - Conducted a rigorous program of research to guide the new regulations on HAPs emissions from natural gas and diesel engines; these regulations were just issued in draft form by the EPA.
- The EECL has capabilities for measuring criteria pollutants (NOx, SOx, CO, HC) and toxic pollutants (formaldehyde, acetaldehyde, acrolein, BTEX compounds, etc.). The EECL was one of the very first engine laboratories to utilize Fourier Transform Infrared

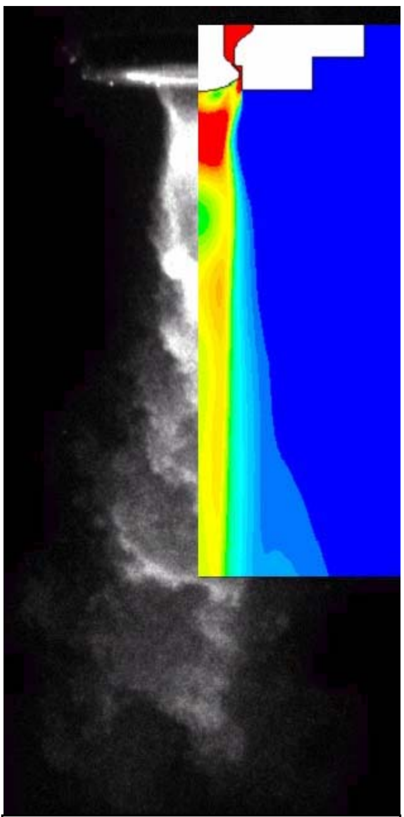
Spectrometry (FTIR) to measure emissions from engines, and continues to develop new techniques to improve FTIR analysis. This includes recent development of newer techniques for even more sensitive measurement of low-concentration toxic compounds. Due to its background and measurement capabilities, the EECL was instrumental in the development of the recent EPA "MACT Rule" for large stationary natural gas and diesel engines

Stationary Source Technologies

The EECL is the most active university in the United States working to understand emissions formation in stationary engines and to develop new technologies for reducing emissions and fuel consumption from stationary engines. The primary applications are engines used for natural gas compression and electric power generation.

Large Engine Studies - The EECL has established the world's only university-based facility for conducting experimental research on large engines. The value of this facility is estimated at over $5 million. Recent key accomplishments from this facility include:

- *Large Bore Engine Testbed* - Further development / improvement of the "Large Bore Engine Testbed" for conducting research on the very large slow-speed engines (300-400 rpm) used on the nation's natural gas pipeline system, typically 1,000 – 8,500 hp.
- *Industrial Engine Research Facility* – Established for conducting research on the large (500hp – 2300 hp) medium-speed engines (900-1800 rpm) used for distributed power generation and industrial applications.
- *Optical Engine Facility* – Established to allow laser-based diagnostics of mixing, combustion, and pollution formation phenomena in large engines. This is believed to be the world's largest optical access engine.
- *Computational Fluid Dynamic* – Capability established to perform detailed computational studies of mixing, combustion, and pollution formation in internal combustion engines. The CFD results are compared closely with optical imaging to ensure the validity and relevance of the computational work.



Comparison of PLIF imaging (left) and CFD results (right) for high pressure fuel injection.

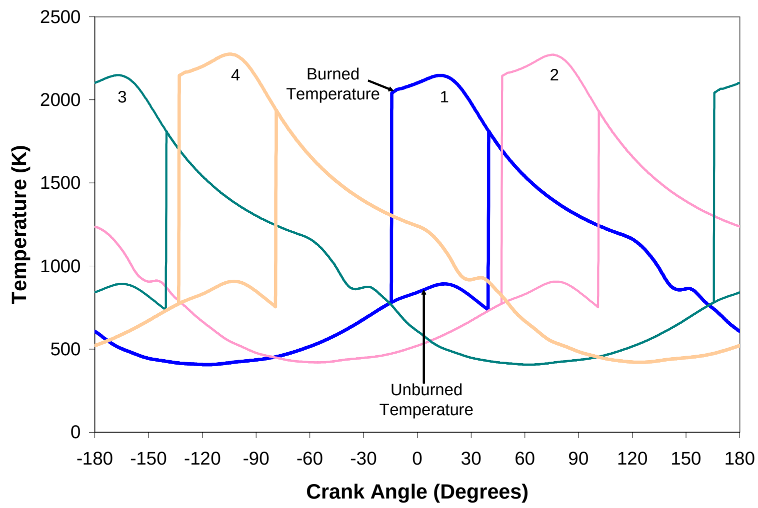
High-Pressure Fuel Injection – The EECL pioneered the application of "high pressure fuel injection" for large natural gas engines, with the first publication on the topic in 1998. The technology is now being rapidly commercialized and is credited with allowing simultaneous reduction in emissions and fuel consumption on the US natural gas pipeline system. Research on high-pressure fuel injection includes:

- Development / documentation of the technology to simultaneously reduce: NOx emissions by 60%-90%, HAPs emissions by 25%-40%, fuel consumption by 6%-9%, and greenhouse gas emissions (CO_2 and methane) by over 25%.

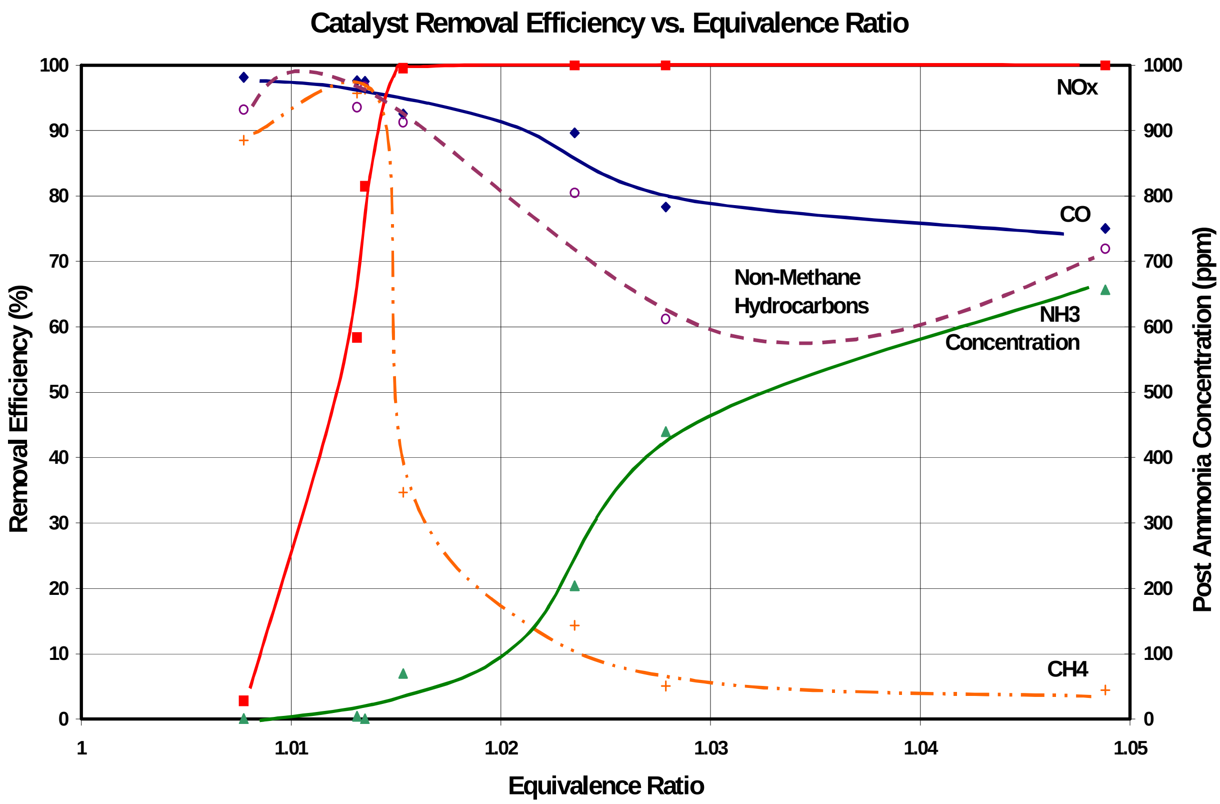
- Technical support for commercialization by companies in Colorado, Texas, New York, and Austria.
- Establishment of a program of advanced optical diagnostics and computational fluid dynamic analysis to further improve the technique.

Other Areas

- *Laser Ignition* – to explore the potential of using focused lasers to replace the spark plugs currently in use in large natural gas engines. This project is a large effort working with DOE, the California Energy Commission, Argonne National Lab, the National Energy Technology Lab, the Oak Ridge National Laboratory and several engine manufacturers. Successful single cylinder tests were performed at the EECL on slow speed and medium speed natural gas engines.
- *Pilot Ignition* – to explore the utilization of minute quantities of diesel fuel to replace the spark plugs currently used in large natural gas engines. A prototype pilot ignition system for large bore natural gas engines was developed at the EECL in collaboration with industrial partners. It was demonstrated on a Worthington SUTC 10 cylinder engine in a compressor station in Window Rock, AZ.
- *Chemical Kinetics* – modeling capabilities developed to model combustion and pollutant formation. Simplified kinetic mechanisms are used in CFD modeling. Complex (>300 reactions) are modeled with chemical kinetics software to for detailed examination of the formation process. Plug flow reactor was built to determine experimentally the lower temperature limit of formaldehyde formation.
- *Engine Simulation* – utilize engine simulation software to gain better insight into engine behavior and design new engine components. Ricardo WAVE was used to model two large bore natural gas engines. A tuned exhaust manifold was designed using Ricardo WAVE.
- *Catalyst and Aftertreatment* – to explore improvements to catalysts and exhaust aftertreatment. This work includes consideration of 3-Way (NSCR), oxidation and SCR catalysts, regenerative NOx traps, and non-thermal plasmas.



Ricardo WAVE engine simulation results for the Cooper-Bessemer GMV-4TF large bore natural gas engine show a significant difference in peak combustion temperatures due to exhaust pressure dynamics. These results explained measured differences in NO_X emissions from the 2-4 vs. 1-3 engine banks.



NSCR testing performed at the EECL on a 4-stroke Superior 6G-825 naturally aspirated engine (900 rpm, 495 hp) used for gas production. The results show a narrow equivalence ratio band for effective reduction of all emissions constituents and significant ammonia formation for rich equivalence ratios. Subsequent research showed that the optimal equivalence ratio band can be widened using a new A/F ratio control technique known as "dithering".

Areas of Current Research Focus

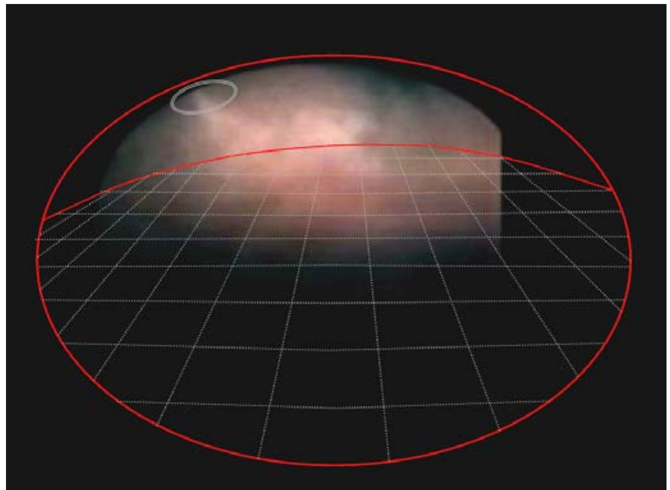
The EECL is working in a broad array of research areas. Current focus areas within the research area of gas engines are described here.

Ignition in Industrial Engines

There are two primary areas of ignition research, laser ignition and precombustion chamber ignition. High energy pulsed lasers are being investigated as a means to ignite very lean mixtures in high BMEP engines. Most agree that fiber delivery of the laser light is an enabling technology for this ignition approach. In June of 2005 the CSU research team became the first in the world to run an engine cylinder using a pulsed laser ignition system that employed hollow core fibers to deliver the laser light. Precombustion chambers are an established

Laser spark formation via a hollow core fiber.

ignition technology for large industrial natural gas engines. However, to meet more stringent emissions regulations prechamber performance must be improved and NO_X generation in the prechamber must be mitigated. As part of this effort the CSU EECL has developed an optically accessible head for our GMV-4TF engine for evaluation of new prechamber concepts. Other diagnostic tools being employed are fast sampling of prechamber gas and spectroscopic analysis of combustion emitted light.



Imaging of prechamber flame jet in GMV-4TF engine at 11°ATDC. Prechamber nozzle is at upper left. Superimposed 1"x1" grid across bottom of head and outlined viewing window give perspective.

Exhaust Aftertreatment for Industrial Engines

The primary areas of emphasis in exhaust aftertreatment at this time are nonthermal plasmas and Selective Catalytic Reduction (SCR). Both are targeted for lean burn applications. In the area of nonthermal plasmas a number of different approaches are being investigated. These include different plasma sources as well as various methods for treating the exhaust. On-going testing involves the marrying of nonthermal plasma and SCR technology by creating a nonthermal plasma from the ammonia reductant stream in a standard SCR configuration. In conventional SCR research the CSU EECL is in the early stages of a multi-year program. This research focuses on large bore two-stroke compressor engines. In this work a slipstream SCR research system is being built on the GMV-4TF engine. This system is designed to enable investigation of state-of-the-art SCR technology, such as pre- and post-oxidation catalysts, hydrolysis catalysts, different reductant types, reductant mixing effects, space velocity, catalyst temperature, and different SCR catalyst formulations.

Distributed Generation

In August of 2005 a 1.7 MW Caterpillar 3516 natural gas engine for distributed power generation was installed at the CSU EECL. The engine is used primarily for engine development work. Current work includes experimental evaluation of ion sensing systems and advanced spark plug technology. There is also on-going electrical grid simulation work. This project involves the installation of various small scale distributed generation sources at the EECL, which include a wind turbine simulator, reciprocating engines, a gas turbine, and a fuel cell. Research will be performed on the stability of the electrical grid as various combinations of these sources are operated through a range of conditions.

Friction Reduction

The goal of this research is to reduce parasitic losses of natural gas reciprocating engines by reducing piston/ring assembly friction without introducing major adverse effects. The work is being performed on a 6 cylinder Waukesha VGF 18 liter engine. Highly precise measurements of FMEP and oil consumption are recorded for various ring pack designs and configurations. Test results are compared with friction modeling performed at MIT.

Gas Composition

Gas fueled engines are typically designed to operate on gaseous fuel composition within a small "window" bounded by methane number and Wobbe index. When the gas composition falls outside this "window" the engine can experience problems with emissions compliance, detonation, fuel system capacity, and engine control. LNG imports, aging natural gas wells, biogas and synthetic gas production, landfill and digester gas supply, and other factors have brought gas composition issues to the forefront. The CSU EECL is performing gas composition research and developing capabilities to expand this research activity. We have installed infrastructure to perform propane blending with natural gas to increase the methane number of the gaseous fuel delivered to test engines. This capability is being used for development of knock detection and control technologies. There are plans to add CO_2 and N_2 blending to simulate landfill gas and to add methane blending to allow full control of methane number.

Biogas

A 4.5 liter 175 HP John Deere 4045 Engine was installed in 2005 at the CSU EECL for biogas research. Specifically, "producer gas" from the gasification of wood is being studied utilizing a Community Power Corporation 15 kW Gasification unit. The fuel is ignited using Diesel pilot fuel injection. The research focuses on three areas: (1) implementing common rail Diesel pilot injection, (2) optimizing timing and duration of pilot fuel injection, and (3) using WAVE modeling for turbocharger sizing.

EECL Staff

When the EECL was founded in 1992, all research was directed by a single faculty member, Dr. Bryan Willson. The laboratory has now grown to include six core faculty members, four Administrative/Professional staff, and a variety of faculty affiliates. The EECL is organized into three functional areas: Technical & Scientific, Administrative, and Operations.

<u>Core Faculty: Technical & Scientific</u>

Dr. Bryan Wilson - Professor of Mechanical Engineering, EECL Director, Founder of the Engines & Energy Conversion Laboratory

Dr. Allan Kirkpatrick - Professor of Mechanical Engineering, Department Head, Dept. of Mechanical Engineering

Dr. Daniel Olsen - Assistant Professor of Mechanical Engineering, Specialties: Large gas engines, emissions reduction, combustion diagnostics, advanced ignition systems

Dr. Charles Mitchell - Professor of Mechanical Engineering, Specialties: Gas Dynamics and Combustion

Dr. Azer Yalin - Assistant Professor of Mechanical Engineering, Specialties: Combustion & Plasmas, laser diagnostics

Dr. Rudy Stanglmaier - Assistant Professor of Mechanical Engineering, Specialties: Diesel engines, fuels, aftertreatment

<u>Core Affiliates: Administrative & Operations</u>

Morgan Defoort - EECL Assistant Director

Kathy Nugent - EECL Administrative Manager

Kirk Evans - EECL Operations Manager

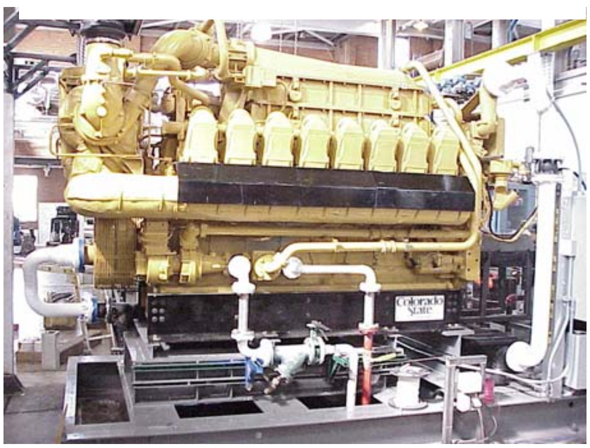
Diana Rose – Administrative Assistant

Faculty Affiliates
Dr. George Collins - Professor of Electrical Engineering, Specialties: Plasmas and diagnostics
Dr. William Duff - Professor of Mechanical Engineering, Specialties: Design of Experiments

Large Industrial Gas Engines at the EECL

2-Stroke Lean Burn Gas Engine
Cooper-Bessemer GMV-4TF

4-Stroke Lean Burn Gas Engine
Waukesha VGF



4-Stroke Lean Burn High BMEP Gas Engine – Caterpillar G3516C

4-Stroke Rich Burn Gas Engine
Superior 6G-825

4-Stroke Lean Burn Gas Engine
Waukesha 3521

Research and development is currently being performed on the Cooper-Bessemer, Caterpillar, and Waukesha VGF engines. The Superior and Waukesha 3521 engines have been moved to storage. They can be re-commissioned if the need arises for research on these engine models.