REDUCE THE COST OF COMPLIANCE BY STAYING IN COMPLIANCE

Woodward adopts industrial gas engine control strategy similar to one that has been successful in the automotive industry

By Alan Oetken and John Felts

Staying within emissions regulations is a fact of life for many operators of natural gas-fueled reciprocating engines. The total cost of staying in compliance includes not just hardware, but also very significant labor costs.

The lifetime costs of an air-to-fuel ratio control and catalyst system are mostly driven by the labor involved with maintaining and documenting the system's long-term compliance.

End users can expect these labor costs to continue to increase as regulatory agencies move to more frequent test cycles, increased monitoring parameters and the associated documentation.

Combustion can only be sustained in a narrow ratio of air to fuel. Stoichiometric refers to the chemically correct ratio of air to fuel, and for natural gas this ratio is around 14.3 by mass.

The term lambda (λ) is used to relate the actual air-to-fuel ratio (air-fuel or AFR) to the stoichiometric air-to-fuel ratio and indicates whether the combustion is rich (more fuel) or lean (more air).

- λ of 1 is a stoichiometric air-to-fuel ratio
- λ greater than 1 indicates a lean condition
- λ less than 1 is a rich fuel condition

Alan Oetken is project manager for New Product Introduction in Engine Systems, Woodward Inc. He has degrees in physics and electrical engineering and started working for Woodward in 1979, spending most of his career in engineering and marketing of energy controls technologies. John Felts is lead application engineer for Engine Systems - Large Engines, Engine Systems, Woodward Inc. He has a degree in electrical engineering and started working at Woodward in 1991. He has developed over 40 different engine control applications and systems ranging from basic speed controls to system compressor controls.

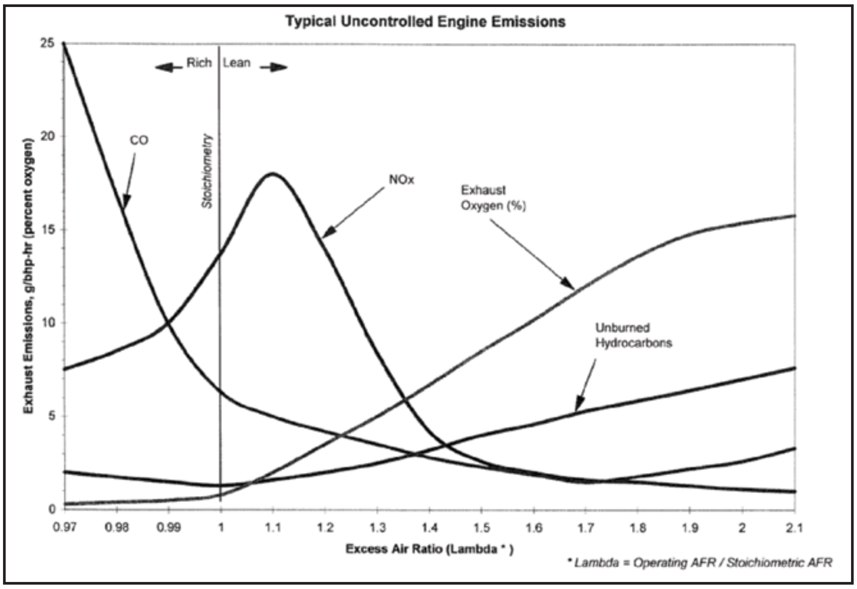

Figure 1. Components of engine exhaust compared to λ

Figure 1 shows the various components of engine exhaust compared to λ.

Spark-ignited internal combustion engine manufacturers take two approaches to meet air pollution requirements:

1. Run the engine lean (λ greater than 1), reducing NO_x (oxides of nitrogen) and CO (carbon monoxide) as long as the ignition system provides enough energy to light the mixture consistently.
2. Run the engine at stoichiometric (λ = 1) and install a three-way catalytic converter in the exhaust to reduce the hazardous air pollutants (HAPs) formed in the combustion process. Three-way catalysts are effective when the engine is operated within a narrow band of air-to-fuel ratios near a λ of 1, but their efficiency drops rapidly outside this narrow band.

One of the major benefits of running at stoichiometric conditions — also called "rich" operation in the industry — is that engine performance is less impacted by the quality of the fuel. This makes rich-burn engines very popular in the oil and gas industry, where the fuel supply has not been refined to pipeline-quality gas.

A second benefit is that the exhaust emissions can be more cost-effectively reduced below levels attainable in lean-burn engines.

The amount of oxygen remaining after combustion gives an indication of the relative amount of NO_x and CO in the engine's exhaust and whether the combustion was rich or lean.

Exhaust gas oxygen (EGO) sensors, when heated to a high temperature, develop an electrical potential difference (like a battery voltage) proportional to the amount of oxygen in the exhaust relative to that in the ambient air. This information, in the form of a voltage signal, can be measured by an

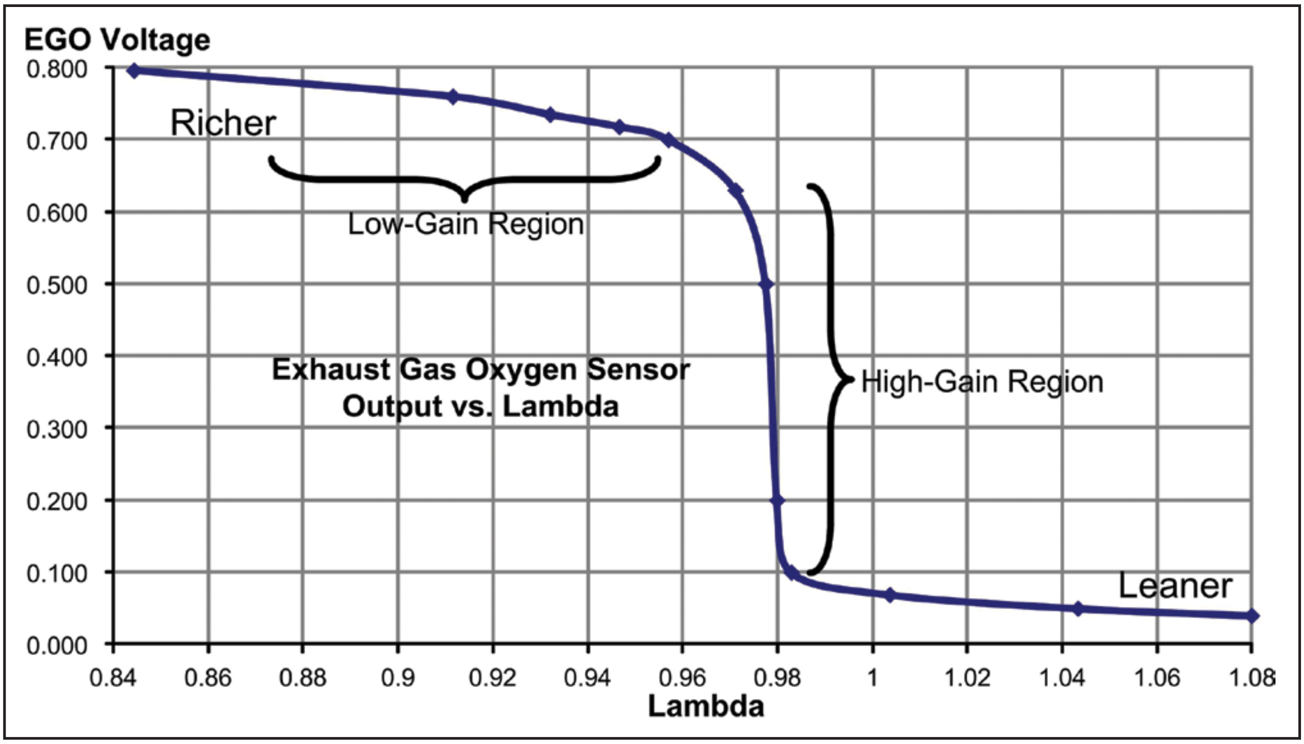

Figure 2. Oxygen in exhaust gas, scaled in lambda, as a function of the output voltage

electronic control unit and used to adjust the engine's air-fuel ratio.

Figure 2 plots the amount of oxygen sensed in the engine's exhaust gas, scaled in lambda, as a function of the output voltage.

The emissions compliance window is defined by the amount of NO_x and CO allowed in the engine's exhaust. Most emissions control approaches in use today on industrial natural gas engines rely on a control setpoint based only on the oxygen content in the exhaust before it enters the catalytic converter. Ideally this setpoint is established at the intersection of the CO and NO_x curves shown in Figure 3. This point is a bit on the rich side of stoichiometric.

The setpoint control unit compares a desired oxygen level, which corresponds to a desired air-fuel ratio, against the actual amount of oxygen sensed by the EGO in the engine's exhaust before it enters the catalytic converter.

When the desired exhaust oxygen level does not match the actual oxygen level, the setpoint control adjusts the engine's air-fuel ratio to return the measured value to the setpoint. This approach tries to control at a very narrow point of minimum CO and NO_x and doesn't leave much room for measurement variations.

The EGO's output voltage can shift with temperature. So changes in the engine's exhaust temperature can cause the setpoint control to be satisfied at an incorrect value of lambda.

For example, suppose the setpoint control is only satisfied with an EGO voltage of 0.7 volts. In Figure 4, lambda could vary from 0.92 to 0.97 depending on the exhaust gas temperatures, compromising the setpoint control's ability to hold the engine's exhaust within emissions limits.

Most industrial engine control strategies also use an EGO sensor designed for automotive engine applications. These are designed to operate in the high-gain region of the voltage curve.

However, methane in a natural gas engine's exhaust interferes with an accurate oxygen reading, causing the sensing point to shift further up the curve in the rich direction (see Figure 5). Variations in the quality of natural gas can also shift the sensor output, making it even more difficult to control accurately to a specific lambda setpoint.

Also, as the sensor ages, the sensor shifts — requiring the control unit to be readjusted regularly. Then, when a sensor is replaced, the setpoint must be readjusted again. The control unit

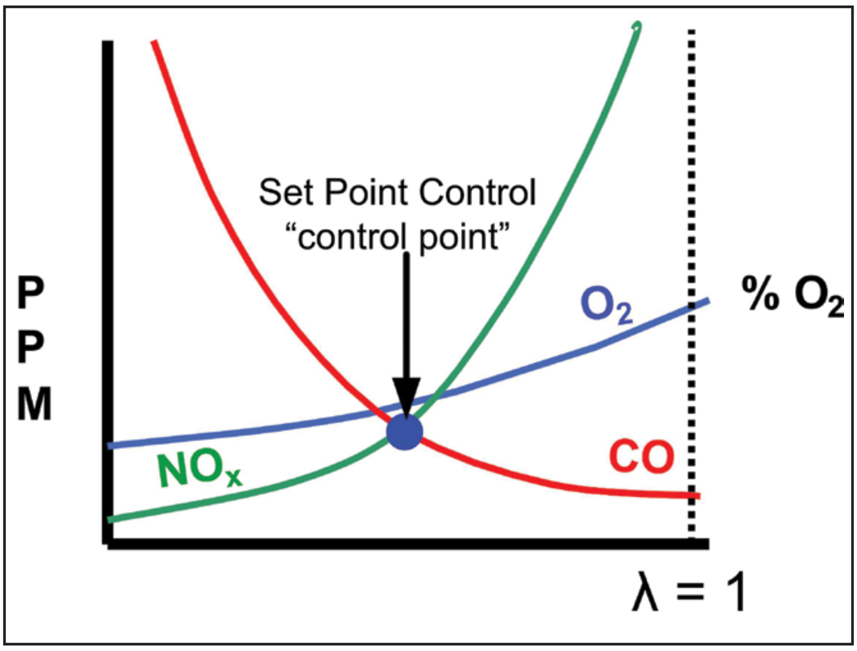

Figure 3. The control setpoint is established at the intersection of the CO and NO_x curves.

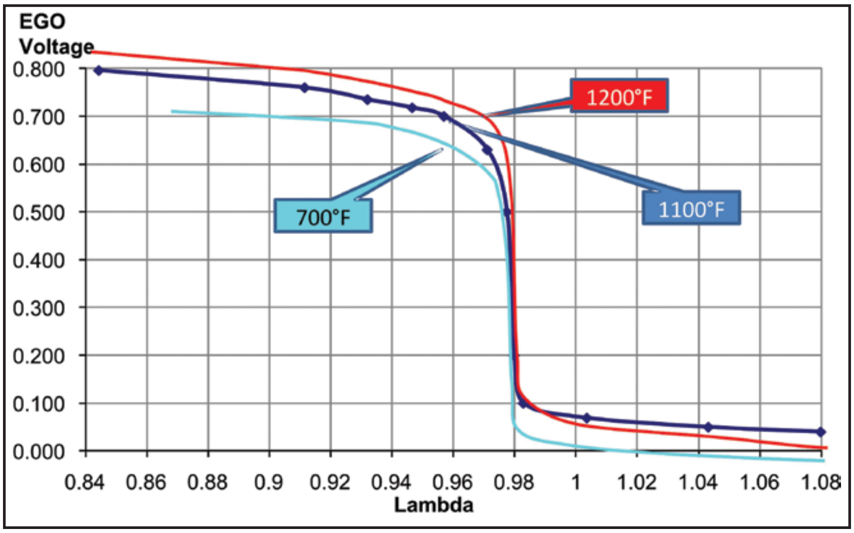

Figure 4. Lambda can very depending on the exhaust gas tempatures.

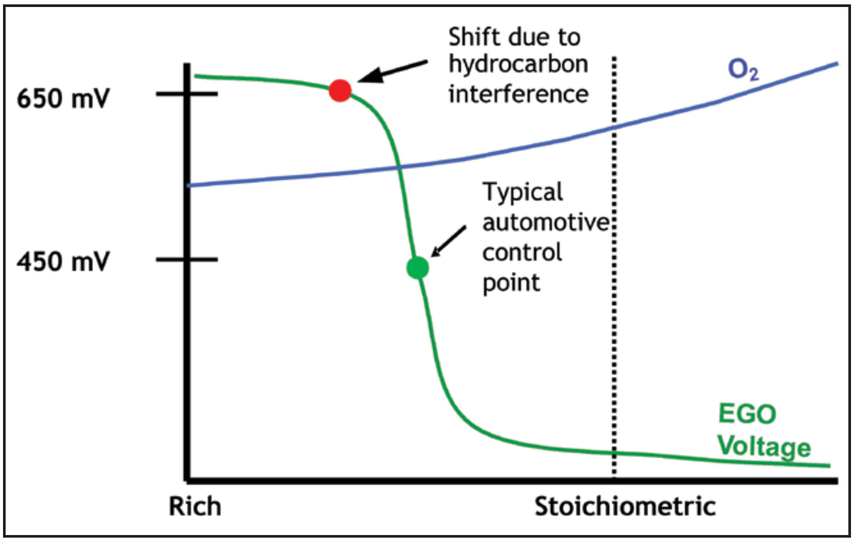

Figure 5. Methane in exhaust can cause sensing point to shift.

can be tuned to perform at a specific set of engine exhaust conditions, but when these change, the engine can go out of compliance.

Clearly the conventional setpoint approach can control the air-fuel ratio of the exhaust entering the catalytic converter, but it cannot guarantee exhaust emissions will stay in compliance over days or weeks of engine operation. Consequently, there is always the risk of noncompliance, the associated cost of recalibration and possibly fines.

These issues moved Woodward to adopt an industrial gas engine control strategy similar to one that has been successful in the automotive industry. This approach brings together three key elements that work in harmony to keep natural gas engines in compliance. These three elements — a Stablesense oxygen sensor, Stablesense control software, and a "holistic" approach to engine control — comprise the new Woodward E^3 Rich-Burn control system.

With the exclusive Stablesense oxygen sensor technology, the operating point for the emissions control resides on the vertical portion or high-gain region of the sensor's voltage curve (see Figure 6).

Operating in this high-gain region causes the fuel control's output to fluctuate or dither between rich, for the chemical reduction of NO_x, and lean, for oxidation of CO.

Because a three-way catalyst has the ability to store oxygen for a short period of time, fluctuating the air-fuel ratio increases the catalyst's efficiency and allows the window of optimal emissions control to appear "wider."

Operationally, this makes the system easier to adjust since there is more room for variation. The catalyst easily handles the oxidation and reduction reactions needed to remove the CO and NO_x from the exhaust.

The Stablesense oxygen sensor is designed specifically for natural gas applications, thereby addressing the issue of methane interference in the sensor measurement.

Additionally, while one Stablesense sensor measures the oxygen entering the catalytic converter, a second Stablesense sensor measures the oxygen levels coming out of the catalytic converter to fine-tune the electronic controller's output to compensate for sensor aging effects.

With the E^3 Rich-Burn system, control functionality is expanded to include information from the engine such as speed and manifold air temperature and pressure, which allows the E^3 controller to compensate for the engine's actual operating conditions.

In essence, the control function allows the catalyst to operate at its optimal efficiency point throughout its life. The E^3 controller also compensates for small differences from one sensor to another, allowing for sensor replacement without recalibration.

These major changes in the approach to controlling emissions effectively create an oxygen management system for the catalytic converter, allowing the engine to stay in compliance for years at a time without any readjustment (see Figure 7).

The system also diagnoses an out-of-compliance situation if it should occur. This greatly reduces the need to continuously monitor compliance performance and the activities that go along with an out-of-compliance situation. All of this reduces the costs of staying in compliance.

Gathering more pertinent engine operating information, using the proper oxygen sensors, executing advanced control algorithms and controlling the entire engine operation as a system have proven to be superior to conventional control approaches.

A pair of examples — in two different parts of the United States and in two different types of applications — illustrate the impact this approach can make in reducing costs and enhancing performance.

The first example is on a Caterpillar 3412 engine driving an irrigation pump in southern California. The operator had difficulty keeping its natural gas engine in compliance with local, state and federal exhaust emissions regulations.

Unstable air-fuel control with the conventional technology required a technician to travel to the site weekly to take measurements and "tweak" the control unit back into compliance. Then there were several hours of paperwork that needed to be completed and submitted to the appropriate regulatory agency to document what had been recalibrated.

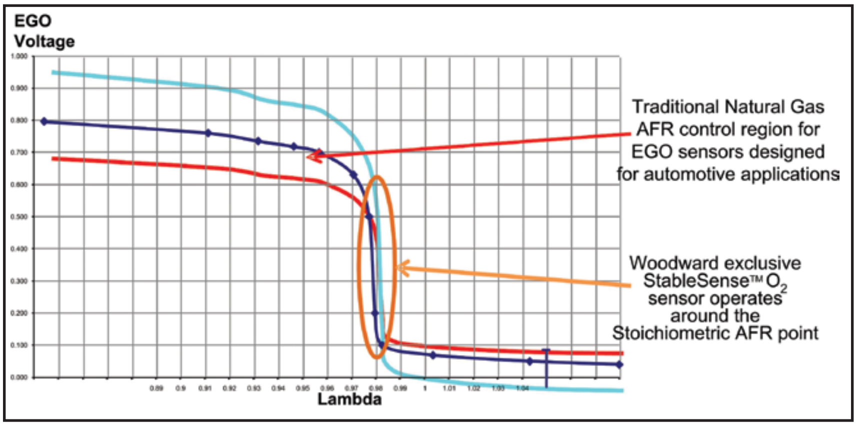

Figure 6. With StableSense, the operating point for emission control is on the vertical part of the sensor's voltage curve.

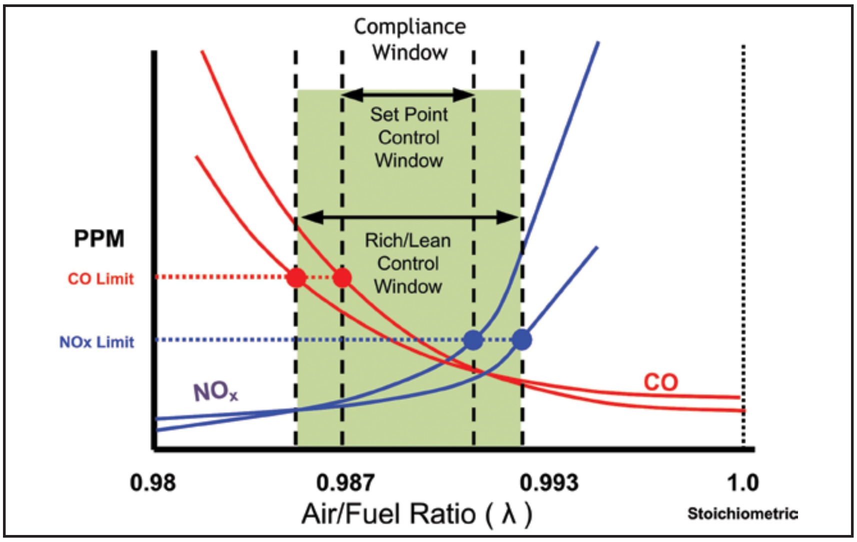

Figure 7. Better oxygen management allows an engine to stay in compliance for years without readjustments.

The engine operator estimated that the costs associated with the engine being out of compliance totaled about 90 hr./mo. Assuming a labor rate of US$50/hr., the total annual cost per engine in their fleet was US$54,000.

That cost was eliminated by installing Woodward's E[3] Rich Burn system with Stablesense technology. The operator's monitoring interval was lengthened from weekly to monthly by the regulatory agency. And with no readjustments required, submittal of follow-up reporting was eliminated.

The engine has been operating continuously in complete compliance without any readjustment for over two years and 8000 hours of runtime, while experiencing all the normal changes in environmental and operating conditions.

The second example is on a Waukesha 7044 engine driving a gas compressor in Wyoming, U.S.A. The operator employs six full-time technicians working 60 to 70 hr./wk. to keep their 400 natural gas engines functioning within an annual compliance testing cycle.

At this pace, technicians could only react to current emergencies. With the state considering increasing the testing cycle from annually to quarterly, the labor costs were expected to increase significantly.

Woodward's E[3] Rich-Burn system with Stablesense technology ensured that the evaluation engine remained in compliance, eliminating the time and expense previously required to bring it back into compliance.

The engine has been operating continuously in complete compliance without any readjustment for over 6000 hours, while experiencing typical changes in environmental and operating conditions.

Woodward's E[3] Rich-Burn system makes it possible for natural gas engines to stay in emissions compliance for years at a time, while providing an immediate indication if the engine does go out of compliance.

The E[3] system also enhances the operation and performance of the engine including: data trending, misfire detection, engine speed/load control, cylinder-bank balancing, fine tuning for ignition timing and improved engine starting.