Report 5: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines

Technical Progress Report
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Abstract

During the fifth reporting period, the main goal for the team was to focus on collecting data to develop Oxygen Sensor Recording System (OSRS) parametric relationships for several rich-burn engines. An air/fuel ratio controller was intergraded with an O_2 sensor. With the use of an Alternative Continuous Emissions Monitoring System (ACEMS) provided by Eastern Municipal Water District (EMWD), the performance will be observed during normal operation.

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Introduction

The objective of this project is to identify, develop, test, and commercialize emissions control and monitoring technologies that can be implemented by exploration and production (E&P) operators to significantly lower their cost of environmental compliance and expedite project permitting. The project team will take considerable advantage of the emissions control research and development efforts and practices that have been underway in the gas pipeline industry for the last 12 years. These efforts and practices are expected to closely interface with the E&P industry to develop cost-effective options that apply to widely-used field and gathering engines, and which can be readily commercialized.

The project is separated into two phases. Phase 1 work establishes an E&P industry liaison group, develops a frequency distribution of installed E&P field engines, and identifies and assesses commercially available and emerging engine emissions control and monitoring technologies. Current and expected E&P engine emissions and monitoring requirements will be reviewed, and priority technologies will be identified for further development. The identified promising technologies will be tested on a laboratory engine to confirm their generic viability. In addition, during Phase 2 a full-scale field test of prototype emissions controls will be conducted on at least ten representative field engine models with challenging emissions profiles. Emissions monitoring systems that are integrated with existing controls packages will be developed. Technology transfer/commercialization is expected to be implemented through compressor fleet leasing operators, engine component suppliers, the industry liaison group, and the Petroleum Technology Transfer Council.

Research Progress

The primary effort during this reporting period was to focus on Task 3, provide a complete analysis of the data recorded from several rich-burn engines fitted with NSCR.

Task 3: Assess Control and Monitoring Technologies

Test Results – Oxygen Sensor Recording System (OSRS) Mapping

A summary of the OSRS mapping results follows.

Test Engines

The team collected data for the following engines to develop OSRS parametric relationships in the following order:

Engine # 62, Cat G379NA, V type, driving a pump
Engine # 65, Cat G42NA, inline type, driving a pump
Engine # 92, Cat G398NA, V type, driving a pump

A review of the results follows.

Test Repeatability

As reflected in Figure 1, the air-to-fuel ratio controller (AFRC) generally does an excellent job of maintaining the lambda value at the desired setpoint. However, the Reference Method paramagnetic analyzer exhibited ~0.08% O_2 measurement uncertainty between the first and second runs. The test team made no change to the analyzer other than momentarily purging the unit and running calibration gas through it without adjustment and then returning it to the stack. This non-repeatability represents ~20% of the permit limit. The very high range of the lowest available calibration gases (typically ~12%) compounds the problem, resulting in measurements <5% of the span gas range. Neither EPA nor SCAQMD has any minimum range requirement for dilutant gases. Unit 65 exhibited very similar performance with a measurement uncertainty of ~0.08% O_2 (Figure 2). Other engines generally exhibited better repeatability (Figure 3).

Lambda Sensor output vs O_2 and Load Sensitivity

For a given lambda senor output, total O_2 in the exhaust generally varied as a function of engine load (Figures 4, 5, and 6). Depending on the individual engine, total O_2 might either increase (Unit 62) or decrease (Unit 65) with load. A review of the mechanisms and then some examples follow.

Load Related Mechanisms

Three factors come into play. At high load higher gas velocities result in a lower residence time within the catalyst. This can result in increased NO_x with marginally sized catalysts. This shorter residence time decreases the heat lost in the pre-catalyst piping. The hotter catalyst inlet temperatures favor greater NO_x reduction. Part load operation may result in incomplete combustion in the engine, increasing the fraction of partially burned or unburned fuel in the exhaust. This increases the total O_2 in the exhaust. However, completion of those oxidation reactions in the catalyst significantly increases catalyst temperature, resulting in greater NO_x reduction.

Unit 62

As expected, even when *total* O_2 exceeds 0.5% the NO_x remained within limits. For example even though total O_2 exceeds 0.5% for Unit 62 at lambda values below ~0.7 (Figure 4), the NO_x (Figure 7) remains well within permit limits of ~200 ppm raw (the equivalent of 59 ppm @15% O_2). In fact for this engine, NO_x approached the limit most closely at minimum load even though the total O_2 was the lowest at ~0.4%. As reflected in Figure 8, this is due to the very low inlet temperature (Figure 8) and reduced reactivity due to this lower temperature as reflected in the low temperature rise (Figure 9).

The engine never exceeded the emissions limit. The trended *net*[1] O_2 data explains this result. *Net* O_2 never exceeded 0.2% (Figure 10). In addition, when trended on a *net* basis, much of the load sensitivity disappears.

Unit 65

The lambda vs total O_2 performance for Unit 65 similarly exhibits load sensitivity. In this case *total* O_2 increases with decreasing load (Figure 2). At reduced load, it proved impossible to obtain 0.5% total O_2. Nonetheless NO_x remained within permit limits at total O_2 levels as high as 1% at minimum load (Figure 5). CO for this engine was quite high, especially at minimum

[1] Net O_2 is based on the measured CO and a conservative estimate of THC of 1000 ppm. In reality, THC is often significantly higher depending on load, probably explaining much of the apparent load sensitivity.

load (Figure 11). This excess CO oxidized with the excess O_2. The resultant *net* O_2 falls within the expected range (Figure 12). The trend properly overstates the *net* O_2, since the THC is expected to be significantly higher than the estimated 1,000 ppm.

At low load, the engine appears to exceed the permit NO_x limit at a lambda setting (~0.75) which roughly correlates with *net* O_2 of 0.4%. The THC in the exhaust is probably much higher than estimated. More importantly, Figure 4e shows that as the engine load drops to minimum the catalyst inlet temperature drops to ~800°F greatly reducing catalyst activity at the lowest (leanest) lambda value achieved. As the engine runs richer (increasing lambda) the inlet temperature drops, probably due to the presence of unburned mixture. This unburned mixture fires in the catalyst resulting in a marked temperature rise across the catalyst (Figure 13). This firing increases catalyst activity resulting in much improved NO_x reduction (Figure 5).

Unit 92

Unit 92 performed very similar to Unit 62. The total O_2 data exhibited some load dependant segregation, approaching 0.5% (Figure 6) at minimum load. The NO_x concentration never exceeded the limit (Figure 14) and *net* O_2 remained below 0.2% (Figure 15). The catalyst inlet temperature dropped to 800°F at minimum load (Figure 16). The catalyst atypically exhibited a temperature rise at all but the leanest, highest load condition (Figure 17). Like Unit 65, the part load temperature rise indicates oxidation of CO and THC increased catalyst reactivity resulting in NO_x reduction despite the low inlet temperature.

Temperature Rise

Contrary to vendors' representations, the Perris catalysts did not necessarily exhibit a temperature "rise." However, the difference between the inlet and outlet temperature exhibits strong dependences on both lambda setting and load (Figures 9, 13, 17). As the lambda value increases (richer), the temperature difference often increased particularly at part load due to the greater activity of the exothermic oxidation reactions from partial combustion. Also, as the load decreases, while the slower exhaust gas velocity results in greater heat loss prior to the catalyst it favorably results in a longer residence time in the catalyst.

Pressure Drop

The pressure drop across the catalyst typically varied from 1.5-5 inches of H_2O depending on the load and lambda setting (Figures 18, 19, and 20). As expected the pressure drop generally increased with load due to the increased mass flow rate. Pressure drop also increased with increasing lambda (richer mixture). The reason is unclear. Mass flow should decrease with increasing mixture richness. Measurement repeatability was fair, even though excellent transducers were used. This is to poor measurement precision at these very low pressure levels.

Subpart E Results

In addition to the OSRS systems, the EMWD has an Alternative Continuous Emissions Monitoring System (ACEMS). During system certification and subsequent remote monitoring, AETC had the opportunity to continuously monitor operation of a state-of-the-art NSCR system. A description of the system and highlights of the results follows.

System Description

The gaseous fueled fired Waukesha P9390 engine generator provides prime power for an isolated at the EMWD's Perris Valley Regional Water Reclamation Facility (PVRWRF). The unit operates continuously on natural gas as necessary during the peak electrical season (June thru October) in an isochronous mode, i.e. with no utility tie in. The unit retains an emergency standby capability on propane.

Engine Particulars are as follows:

Bore:	9.375 in
Stroke:	8.5 in
Output:	1970 BHP (1470 KWe)
BMEP:	138 PSI

A Miratech NSCR Catalyst controls emissions with the following performance:

98.8% NO_x reduction

93.3% CO reduction

91.2% Organics reduction

The catalyst is fully insulated.

A state of the art Woodward Geco/Miratech MEC-2000 Air Fuel Ratio Controller (AFRC) regulates engine air fuel ratio to maintain exhaust O_2 concentration within the required limits. Triplicate O_2 sensors (two upstream, one downstream) ensure optimal controller response.

Typical System Performance

A review of typical system performance follows.

Normal Operation

During normal operation the system dithers with a period of about 1 minute (Figure 21). NCSR systems typically exhibit this performance, due to interactions between the load, governor and AFRC. Such natural dithering may offer some performance benefit by exploiting the storage/regeneration characteristics of the catalyst similar to automotive applications.

Due to minor variations in load and natural governor modulation, the lambda sensors indicate minor variation in AFR. The controller in turn modulates the supplemental fuel valves to maintain the desired exhaust gas constituents. This results in an asymmetric periodic response in which NO_x varies between ~20 ppm (~6 ppm NO_x at 15% O_2) and 35 ppm (10 ppm NO_x at 15% O_2) with an average value of ~26 ppm (7 ppm NO_x at 15% O_2)[2]. Occasionally a larger perturbation occurs resulting in greater NO_x excursions as described below.

Transient Response

The subject engine provides the prime power to the plant load on an isolated bus. The engine instantaneously responds to any and all changes in load on that bus. Grinders at the subject facility cycle approximately once per minute, creating the periodic oscillation in engine load and Air Fuel Ratio Controller (AFRC) settings discussed above, contributing to the system's natural dithering (Figure 22).

Periodically a pump or similar large load comes on-line inducing brief starting "step ups" in load of ~50 kw on 1250 kw nominal (~4%) lasting ~1-2 minutes followed by a return to normal load (Figures 23 and 24). The engine governor instantaneously responds to load changes by opening or closing the carburetor butterfly resulting in momentarily lean (step up) or rich (step down) operation. The lambda sensor detects the resultant deviation in net O_2 in the exhaust and the AFRC alters the volume of supplemental fuel. NO_x emissions will momentarily increase (load step up) or decrease (step down). However O_2 concentration as measured by the CEMS never exceeds 0.5%[3].

In general these emissions excursions last less than the 1-2 minutes of the load excursions themselves due to the response of the AFRC and natural O_2 storage/regeneration in the catalyst. Normal unloading generally does not induce similar excursions (Figure 24). This combination of natural dithering and transient response preclude assessments of compliance on an instantaneous basis. Rather emissions and parametric data must be averaged over a representative period as reflected in the permit, typically 15 minutes or one hour. Most transient excursions largely wash when so averaged and the system satisfies permit requirements.

The overall response of the system, typical of "reactive" control such as supplemental fuel based systems, is quite satisfactory. Further AFRC tuning would probably not improve response. The use of a throttle body or port injection based AFRC capable of better maintaining the total AFR might reduce the problem, but this technology currently does not exist and is not BACT.

Out of Control Operation

In addition to transient variations in NO_x emissions due to system perturbations, the AFRC on NSCR fitted engines can go out of control. Most typically ambient temperature changes altered the bulk carburetor air/fuel ratio, exceeding the control range of the supplemental fuel

[2] The permit limit of 0.15 g/BHP-HR corresponds to ~10 ppm NO_x at 15% O_2.
[3] This partly reflects the slow response time of the paramagnetic analyzer and its poor precision at this low O_2 concentration, hence the use of lambda sensors. More importantly, storage/regeneration in the catalyst probably helps to momentarily maintain O_2 levels during the excursions, which are generally quite small in terms of air/fuel ratio.

valves (Figure 25). After a couple of minutes at this condition O_2 in the catalyst exceeds 1% and the NO_x emissions will go out of control resulting in extremely high emissions values.

To restore control the bulk carburetor air/fuel ratio must be manually re-adjusted to bring the AFR back within the control range of the supplemental fuel valves (Figure 26). Within less than a minute the AFRC restores control and NO_x emissions rapidly return to nominal levels.

In general, a properly tuned and sized AFRC system will maintain compliance unless this out of control condition occurs. The condition is easily detected when the supplemental fuel valves fully open and remain open without the desired richening of the AFR. All modern AFRC's detect and alarm this out of control condition, requiring manual intervention to acknowledge and reset. It is therefore quite easy to detect out of control operation.

Catalyst Seasoning

During initial system mapping, the NSCR system achieved extremely low NO_x emissions at relatively high O_2 levels. The performance rapidly degraded over the span of several hundred hours requiring continual adjustment of the lambda sensor setting. While not well understood, this "seasoning" process can significantly impact lambda sensor setting and parametric relationships based on them. In particular, AETC found that ACEMS relationships based on lambda sensor data gathered immediately after system start up substantially under-calculated NO_x emissions. The team had to develop new relationships after several hundred hours of operation.

Partial Catalyst Testing

In support of ACEMS mapping and QA, the test team removed one half of the catalyst elements and then re-mapped the engine. As noted above, the catalyst was still quite "green" and had not seasoned. Consequently, the absolute reduction values are not necessarily representative. The relative trends however offer interesting insight into catalyst performance.

Removal of half the catalyst elements had limited impact on CO reduction with the majority of the difference within the data scatter (Figure 27). However, NO_x significantly increased (Figure 28) with catalyst element reduction as did the temperature rise (Figure 29). All three reactions of interest, oxidation of CO and THC and reduction of NO_x are exothermic. The oxidation reactions, in particular $CO \rightarrow CO_2$ posses low activation energies. Consequently much of the oxidation reaction, at least that involving the available total O_2 at the catalyst inlet, occurs near the front of the catalyst releasing significant heat. Reduction of NO_x, with its much higher activation energy, occurs later in the catalyst. In fact, the high activation energy may explain in part the seeming lack of temperature rise in some applications. When a temperature rise does occur, it confirms successful oxidation, but does not offer any information on NO_x reduction. In particular the temperature rise data suggests that a decrease in temperature rise indicates greater NO_x reduction.

Full Bypass

The subject engine was fitted with a catalyst bypass check valve to prevent catalyst damage during a backfire. During continuous operation the bypass failed and lifted, fully bypassing the catalyst. The pressure drop decreased by ~0.5 inch of H_2O, but remained within the range of typical operation of 3.5-4.5 inches of H_2O. Without careful scrutiny of the data after the fact, it is almost impossible to detect the change.

This particular installation utilizes a low quality pressure transmitter with poor sensitivity. A higher quality transducer may have rendered better data to somewhat simplify the detection of the problem. Nonetheless, it is doubtful the bypass could have been detected based on pressure drop data alone.

Further Work Planned

During the next quarter, the research team will direct most of its effort on Tasks 4 and 5, which will lay the groundwork for Task 6.

Task 4: Determine Technology and Market Gaps

This task will use the emissions control approaches identified in Task 3.0 to determine the practical targets for the magnitude of emissions reduction in E&P engines. Once the reduction magnitudes are determined, each will be ranked by how applicable it is to the specific inventory of field engines, its expected cost of implementation, and the overall emissions reduction that can be reasonably anticipated from further development and commercialization of the technology.

The second portion of this task will compare the expected emissions reduction performance to the current and expected emissions permitting requirements facing the E&P industry. Doing so will identify the high-impact control technologies that are expected to be widely utilized by the E&P industry, and which should be targeted either for immediate testing, or require more fundamental component development.

Expectations are that this work will center on three major areas: 1) engine controls; 2) ignition systems; and 3) exhaust gas treatment options.

Task 5: Conduct Controlled Tests to Evaluate Promising Technologies

The most promising technologies identified in Tasks 3 and 4 will be tested under controlled conditions on an Ajax engine, which is in very wide use in E&P operations. The tests will most undoubtedly be conducted at Ricardo, Inc. in Burr Ridge, IL. Ricardo operates a set of state-of-the-art, fully instrumented test cells that can accommodate engines up to 1,000 HP. Up to 160 hours of test time at Ricardo are planned to conduct preliminary performance testing of the array of promising technologies identified in Task 3.

Task 6: Determine On-engine Control System and Sensor Requirements for Remote Emissions Monitoring

This task will identify the necessary sensors, software, and hardware to provide remote engine emissions and performance monitoring. The results from Task 3.1 will be used to determine the scope and content of a monitoring system. The project team has expertise in this area, and has actually developed and implemented remote sensing technologies for pipeline engines for what is arguably the most stringent real-time emissions monitoring program in the world (California's RECLAIM program).

Conclusions

The primary conclusions from this quarters work are the catalyst is not the ultimate solution to the emission problem. The catalyst has a break in period, in which the NO_x reading will be very low, but in due time lambda sensor will have to be readjusted to the optimal performance. Nevertheless, once the lambda sensor is set correctly, there is a lag in the catalyst reaction time, which could lead to an out of control operation. Moreover, the current instrumentation is not sufficient to determine if a catalyst is actually working or not. Additionally, this report provides some excellent operation information on lambda sensors and AFRC.

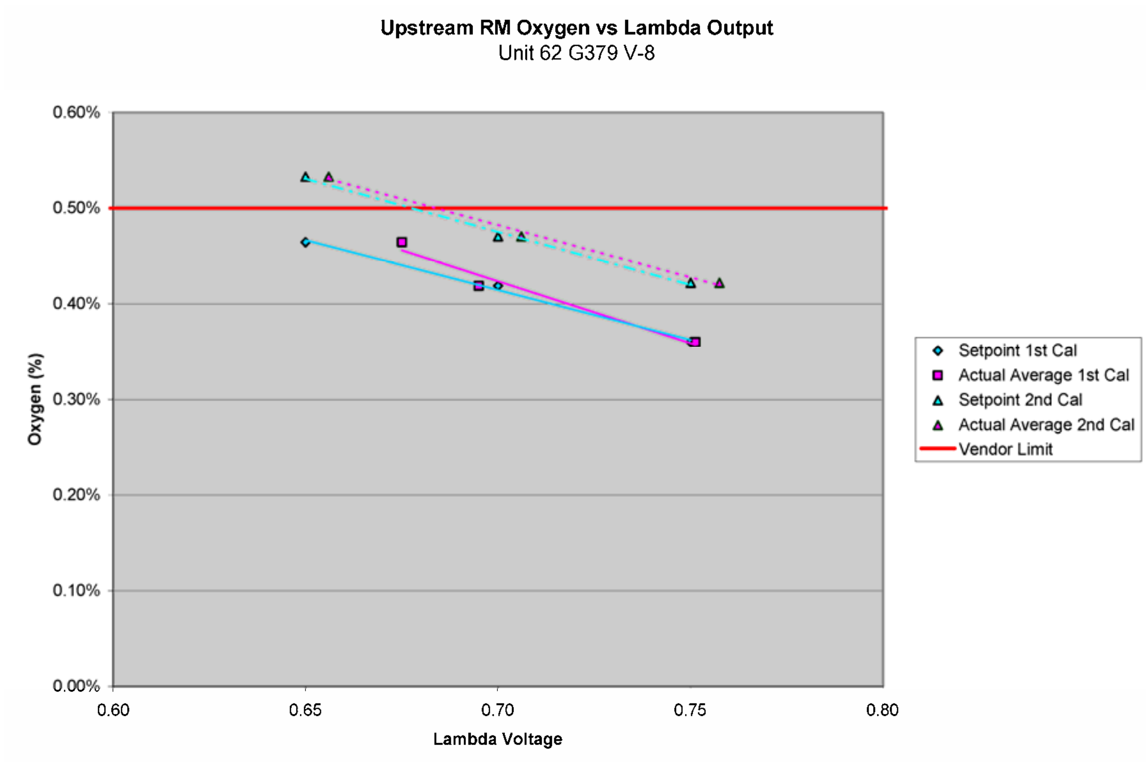

Figure 1: Typical trends of *total* O_2 versus lambda sensor output during calibration.

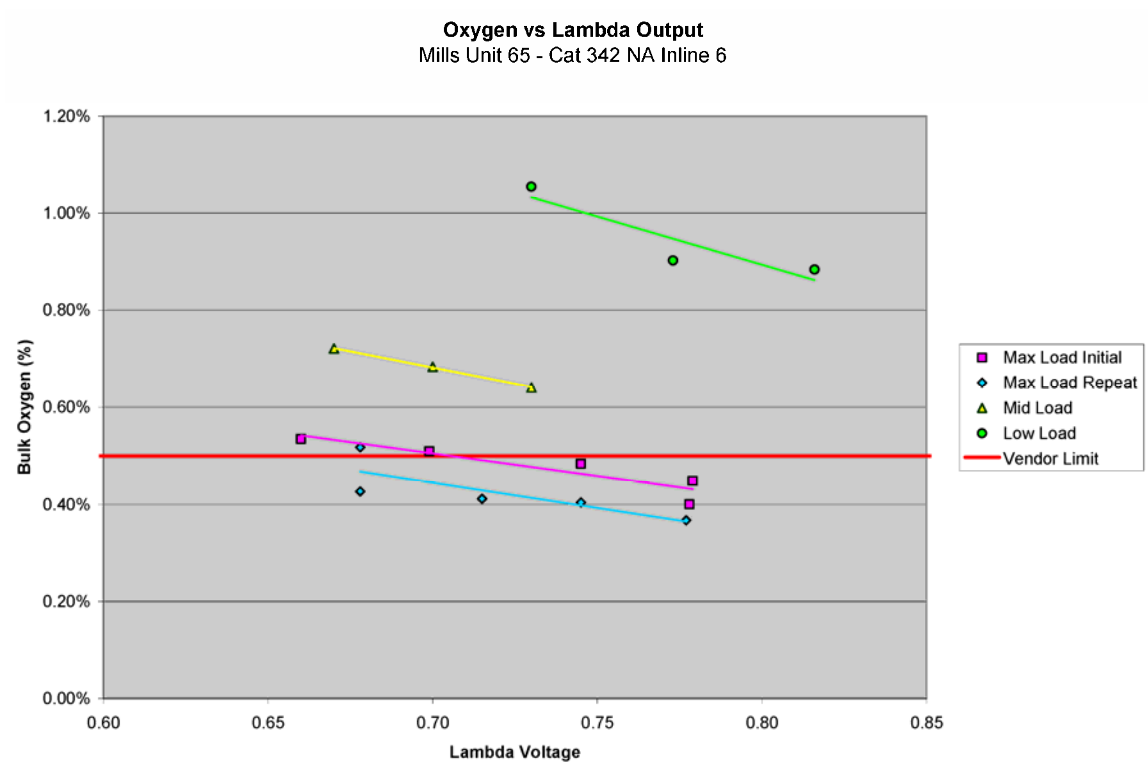

Figure 2: Typical trends of *total* O_2 versus lambda sensor output versus engine load.

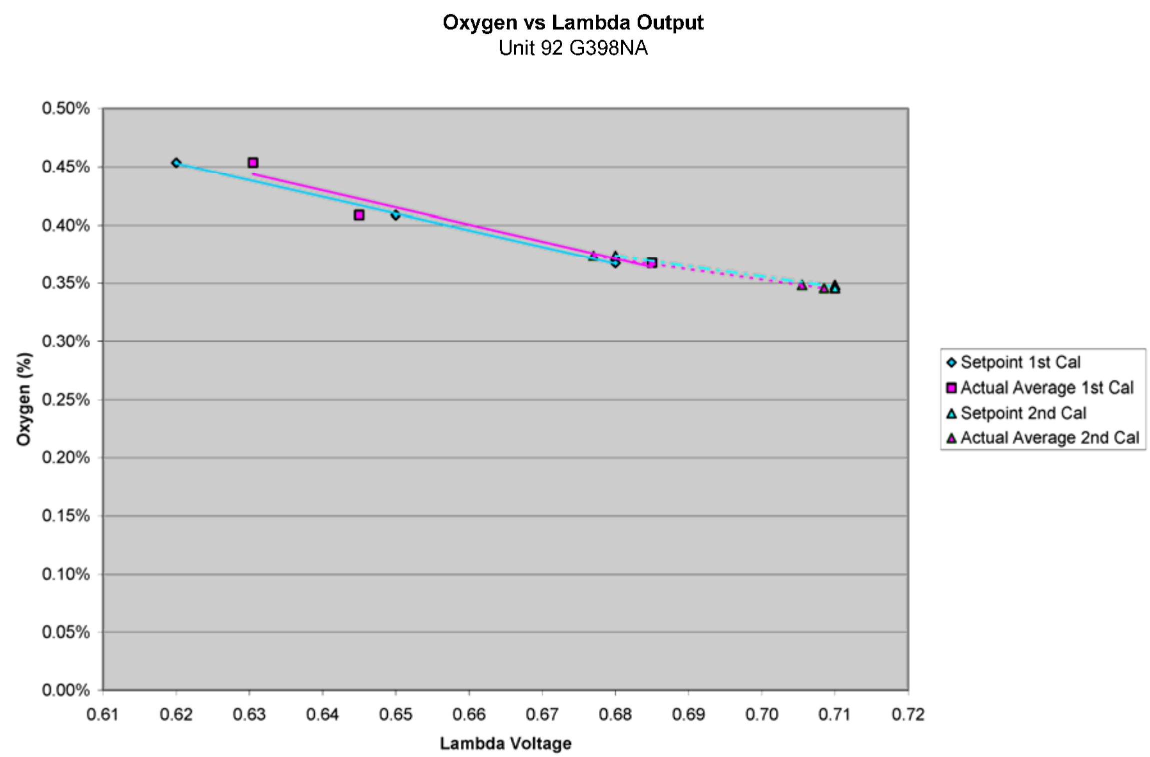

Figure 3: Typical trends of *total* O_2 versus lambda sensor output during calibration.

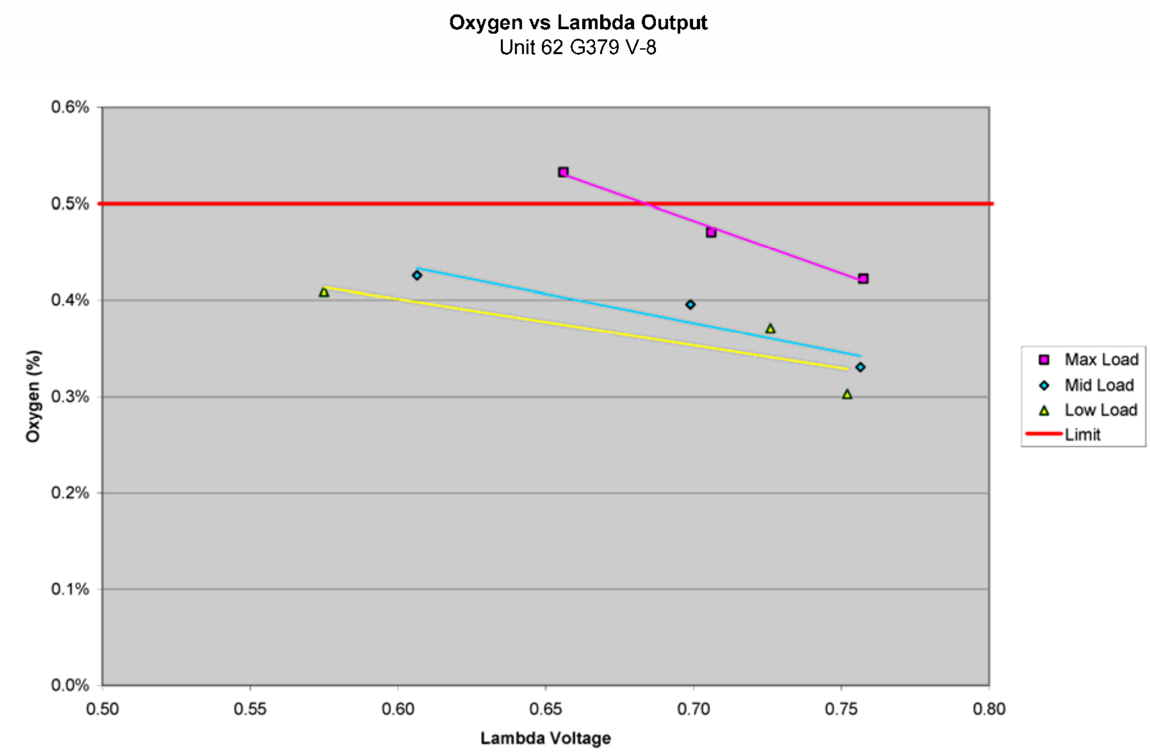

Figure 4: Typical trends of *total* O_2 versus lambda sensor output versus engine load.

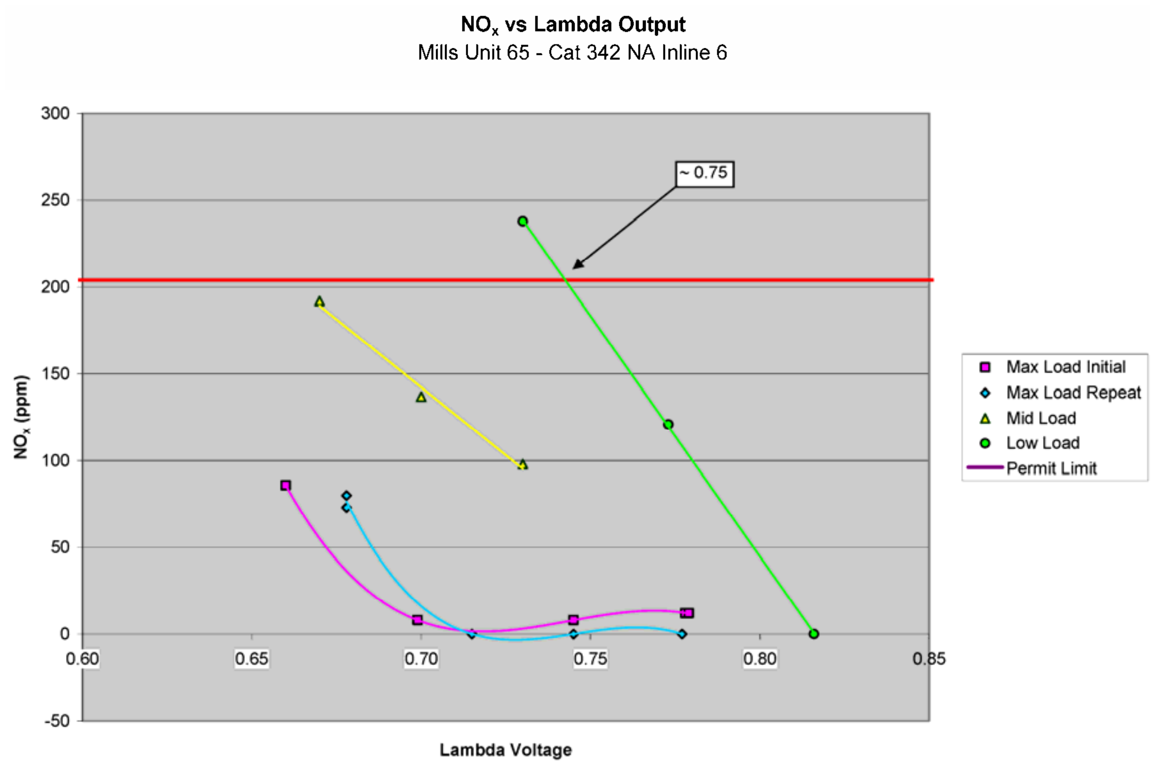

Figure 5: NO_X versus lambda sensor output as a function of engine load.

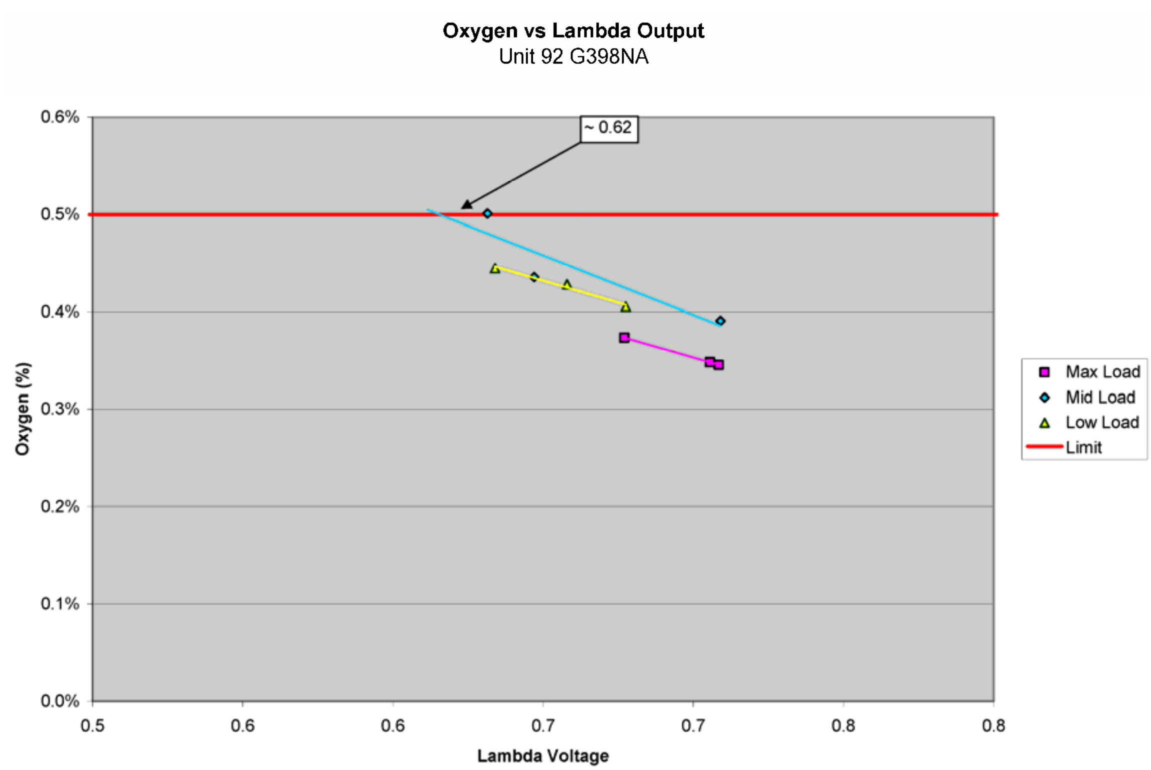

Figure 6: Typical trends of *total* O_2 versus lambda sensor output for engine load.

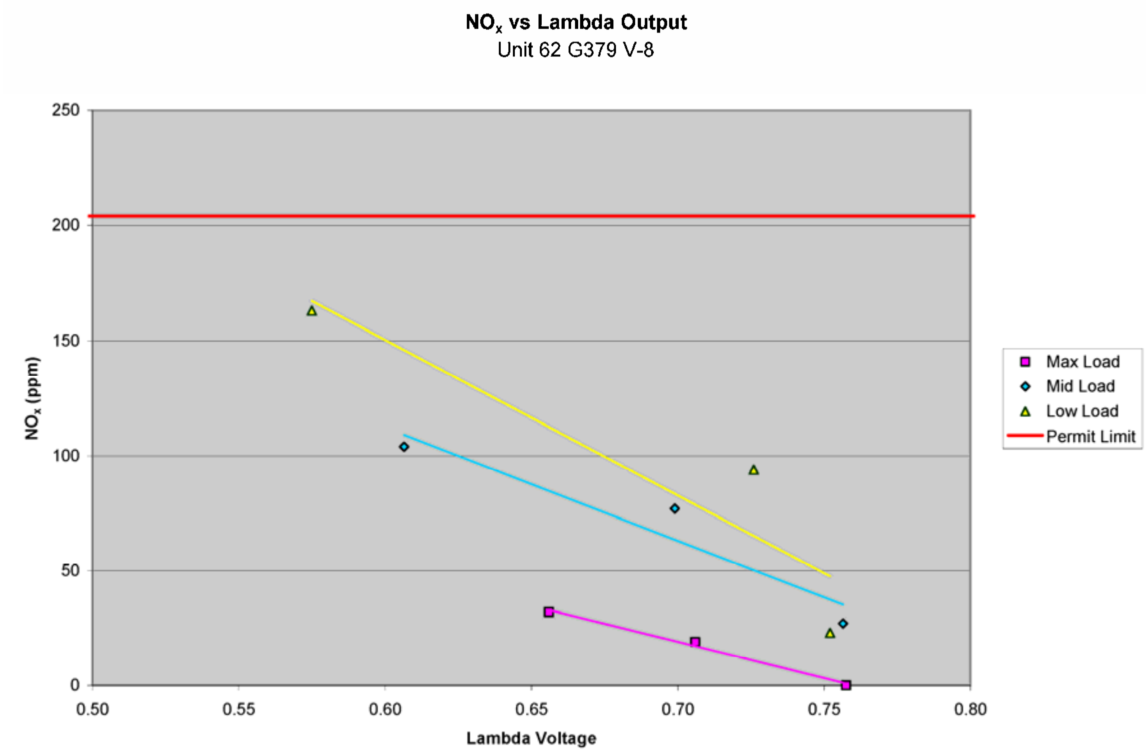

Figure 7: NO_X versus lambda sensor output for varying engine load.

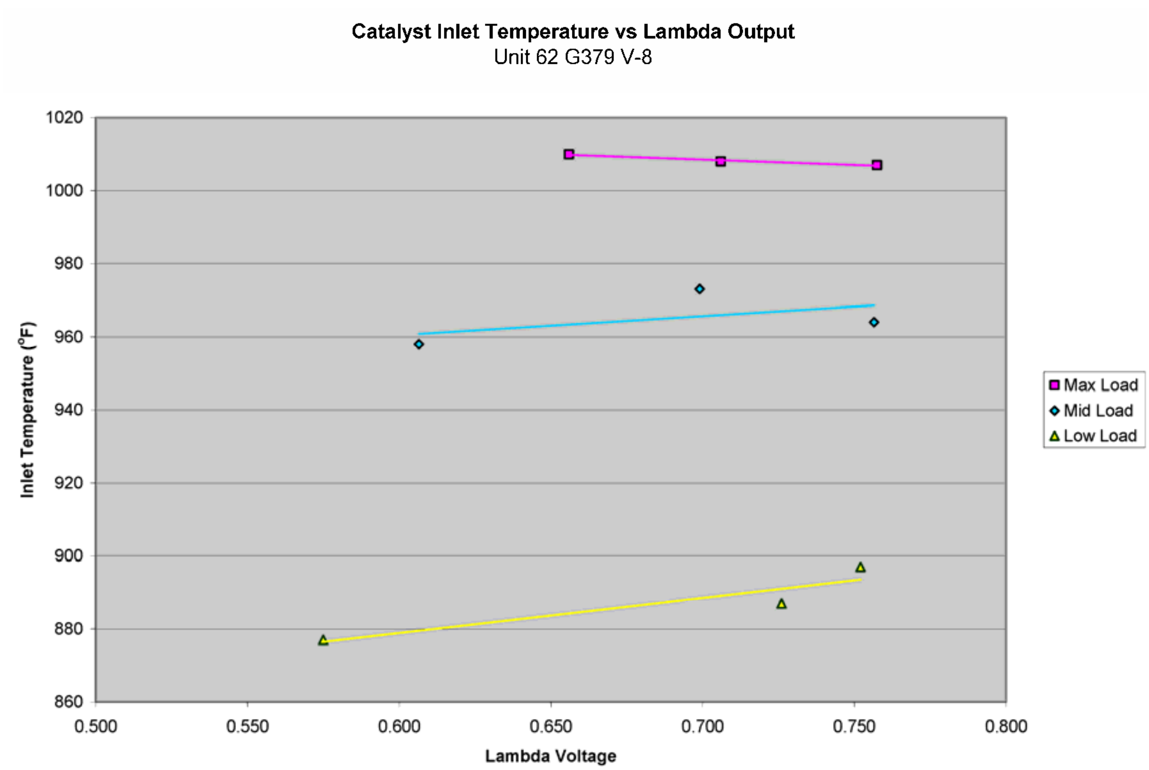

Figure 8: Catalyst inlet temperature versus engine load.

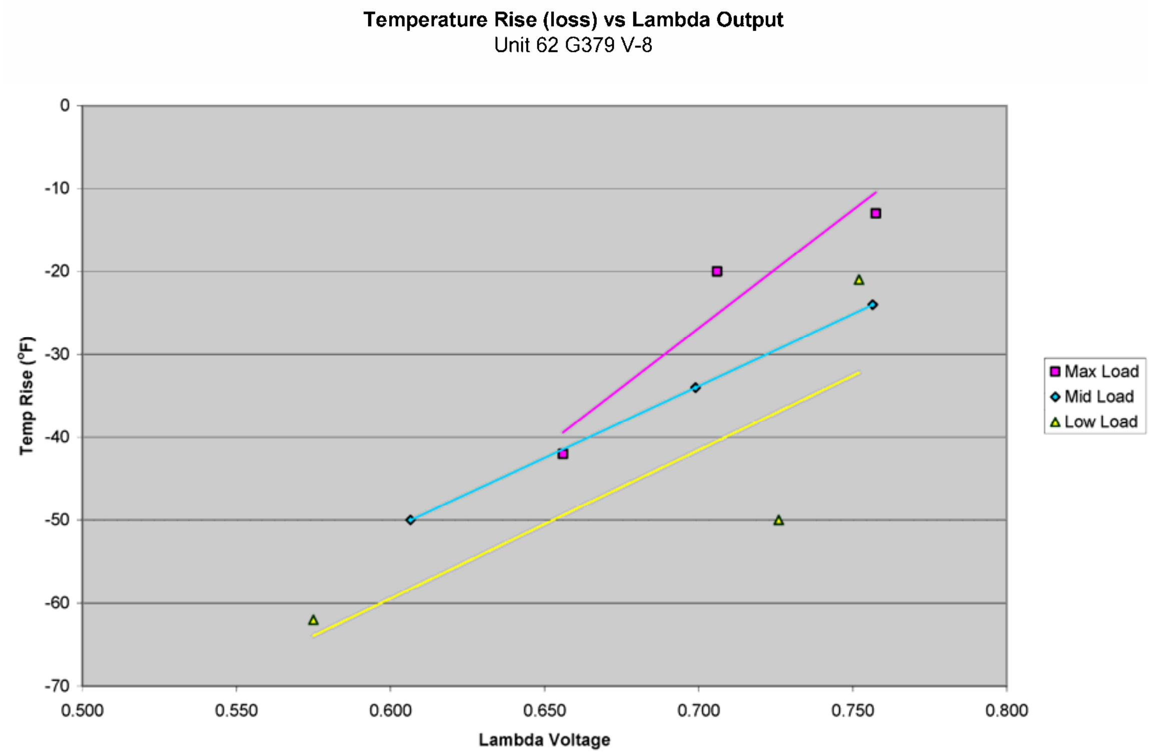

Figure 9: Catalyst temperature rise versus engine load.

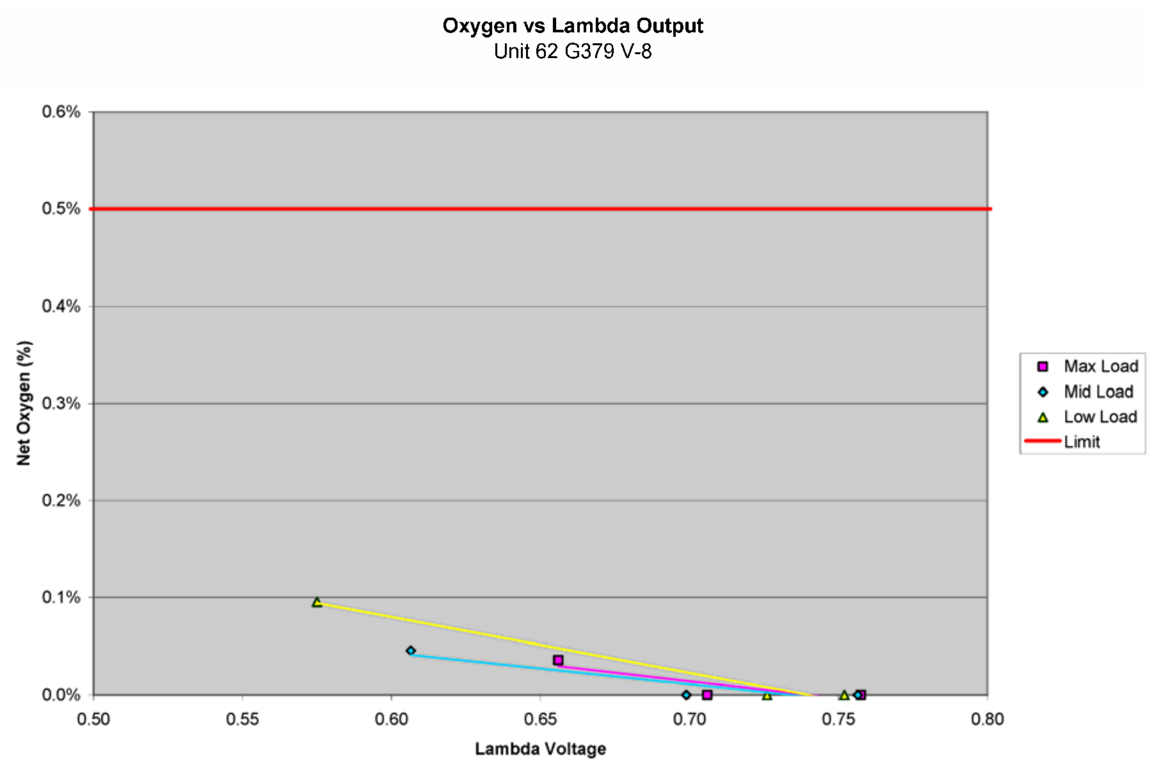

Figure 10: Typical trends of *net* O_2 versus lambda sensor output versus engine load using Figure 4 data.

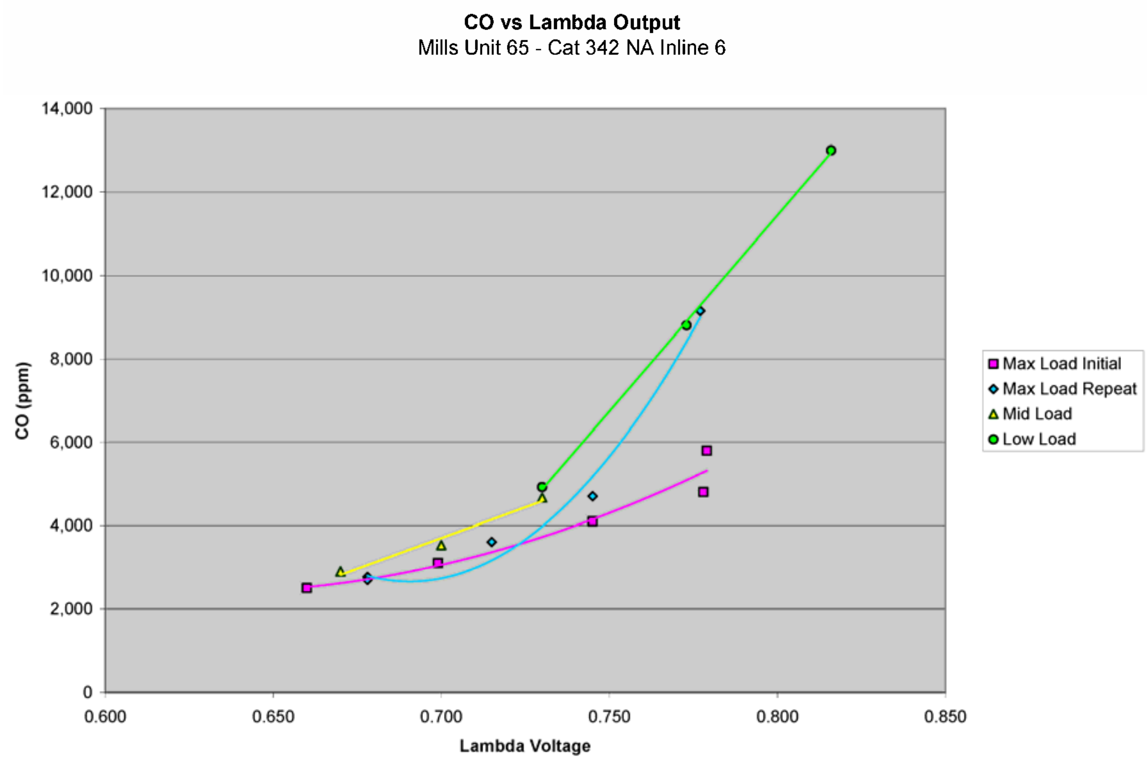

Figure 11: CO versus lambda sensor output as a function of engine load.

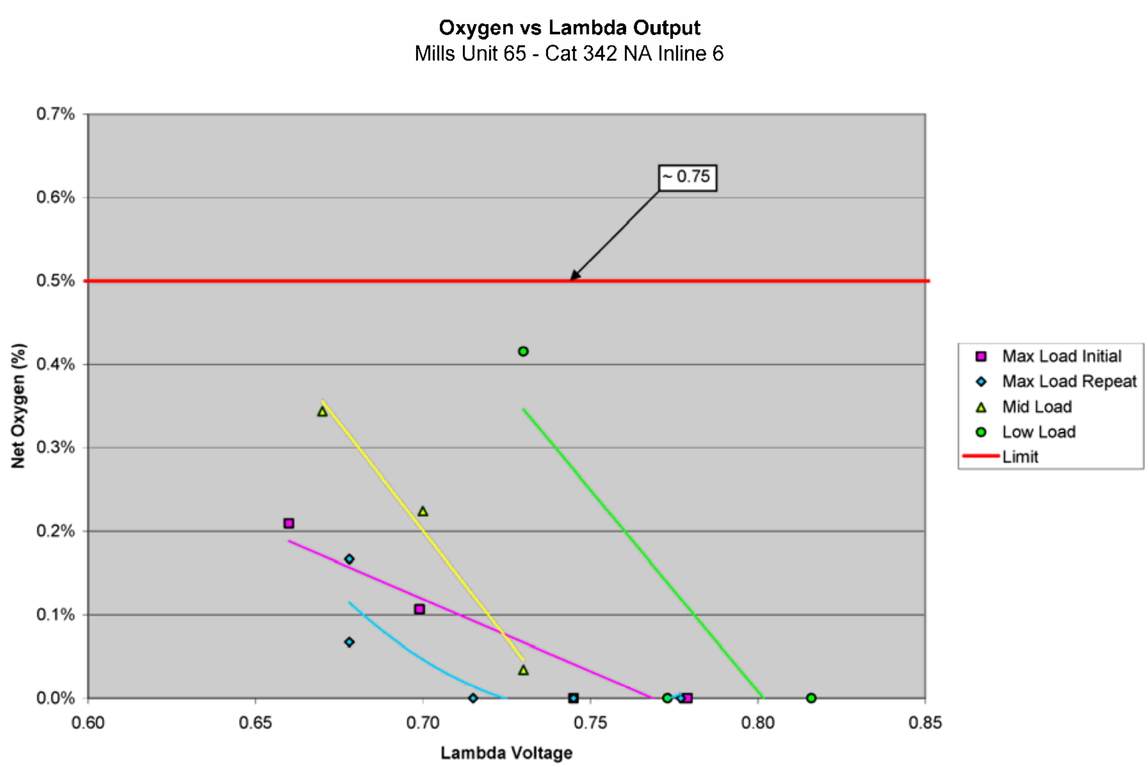

Figure 12: *Net* O_2 versus lambda sensor output as a function of engine load.

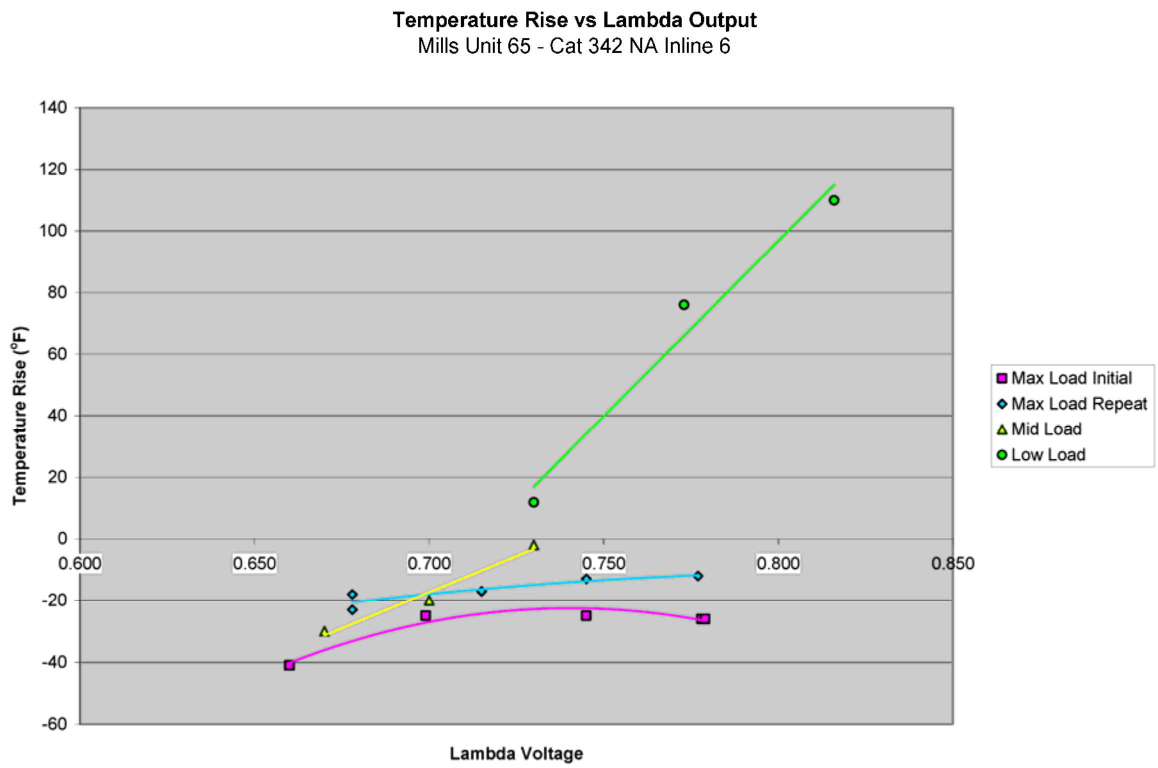

Figure 13: Catalyst temperature rise as a function of engine load.

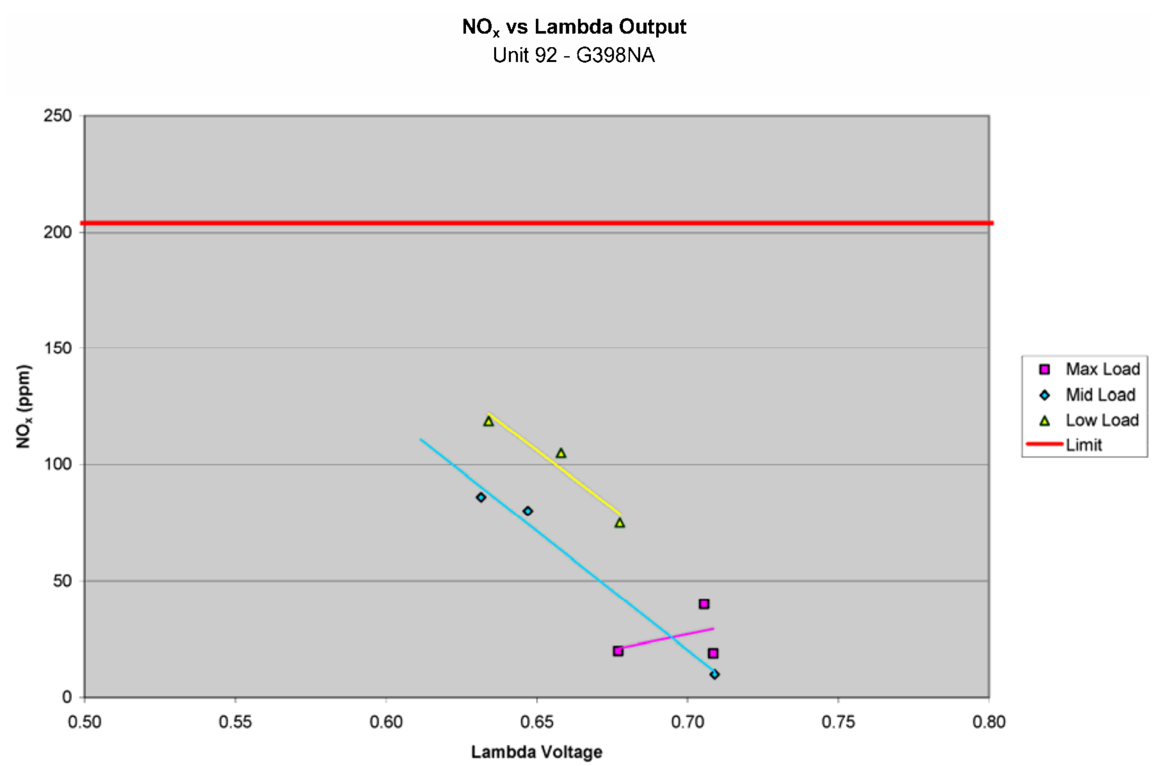

Figure 14: NO_X versus lambda sensor output for engine load.

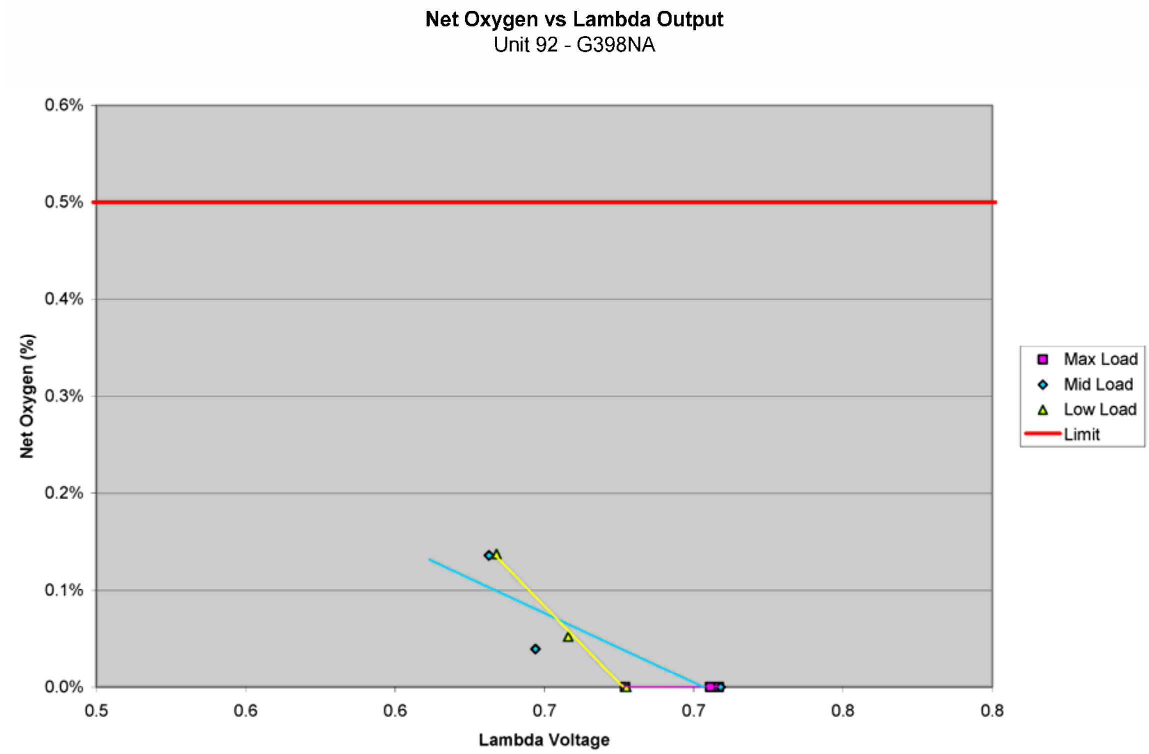

Figure 15: Typical trends of *net* O_2 versus lambda sensor output for engine load using Figure 6 data.

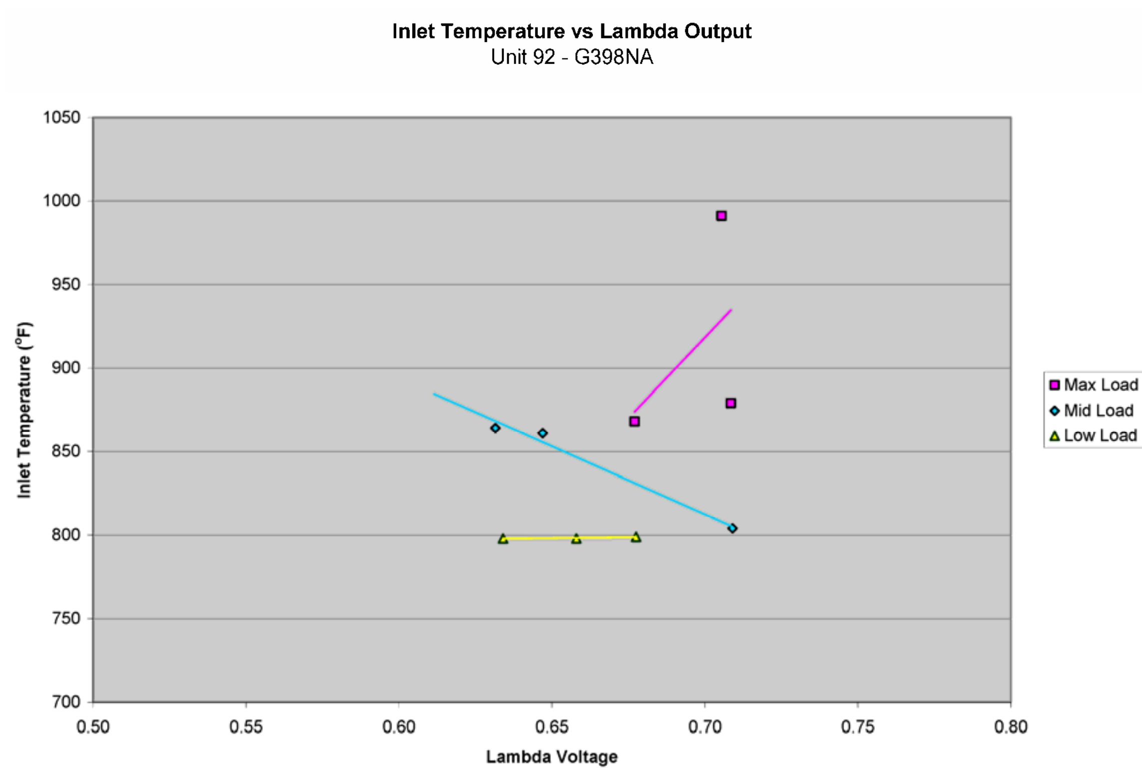

Figure 16: Catalyst inlet temperature as a function of engine load.

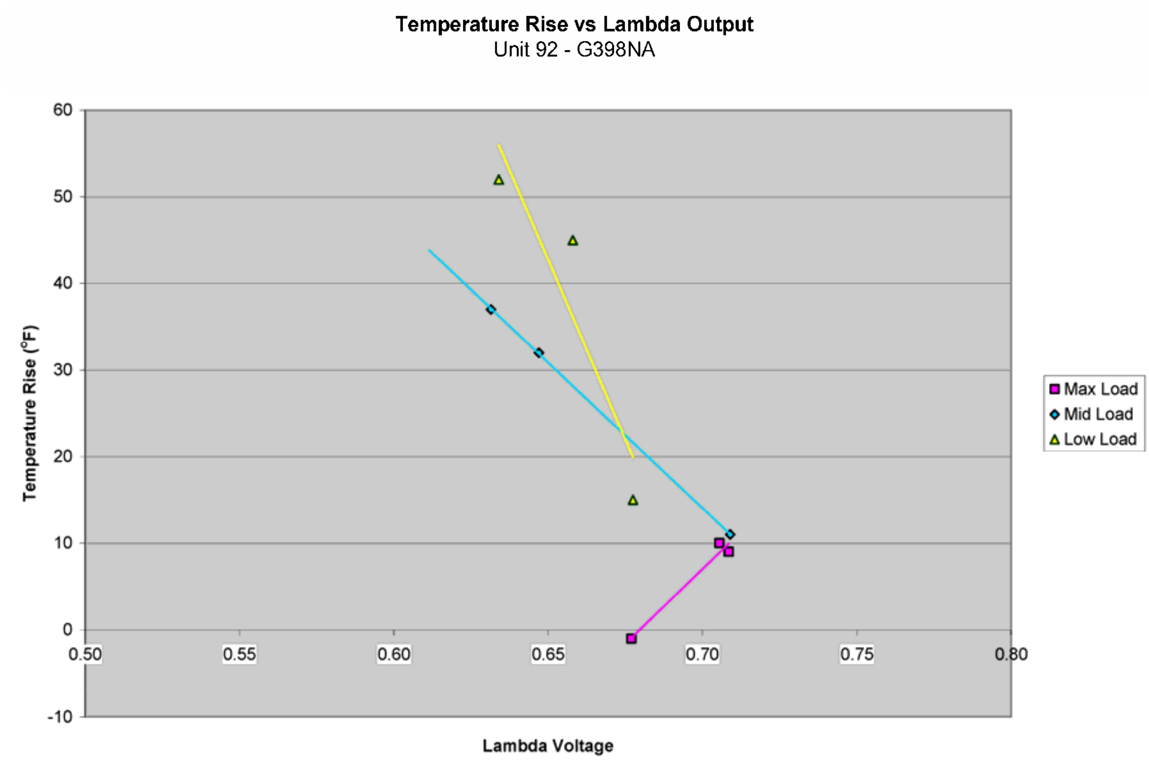

Figure 17: Catalyst temperature rise as a function of engine load.

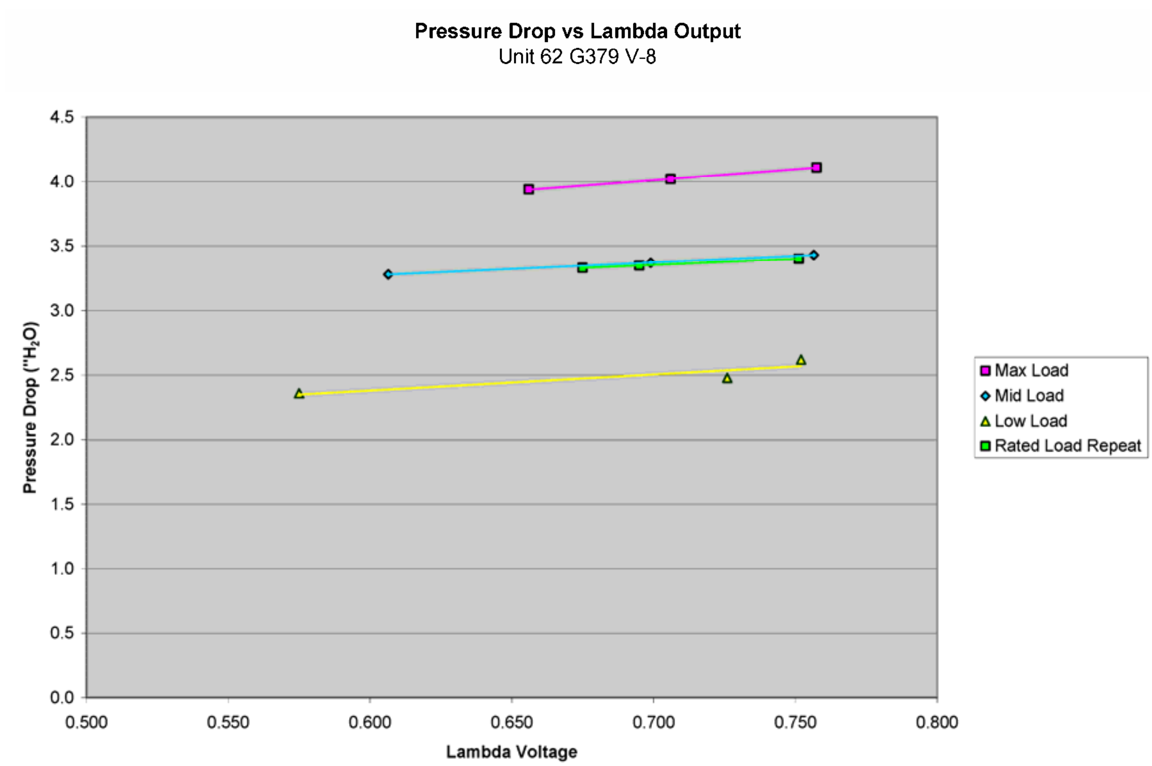

Figure 18: Pressure drop versus engine load.

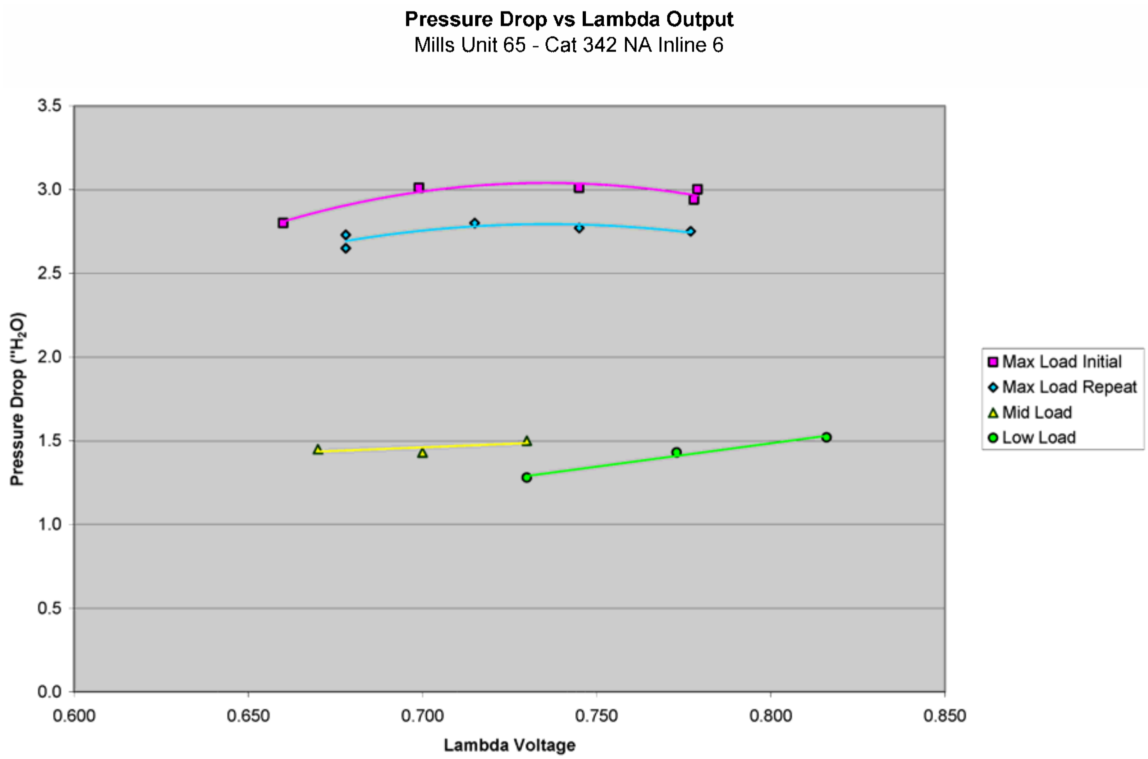

Figure 19: Pressure drop versus engine load.

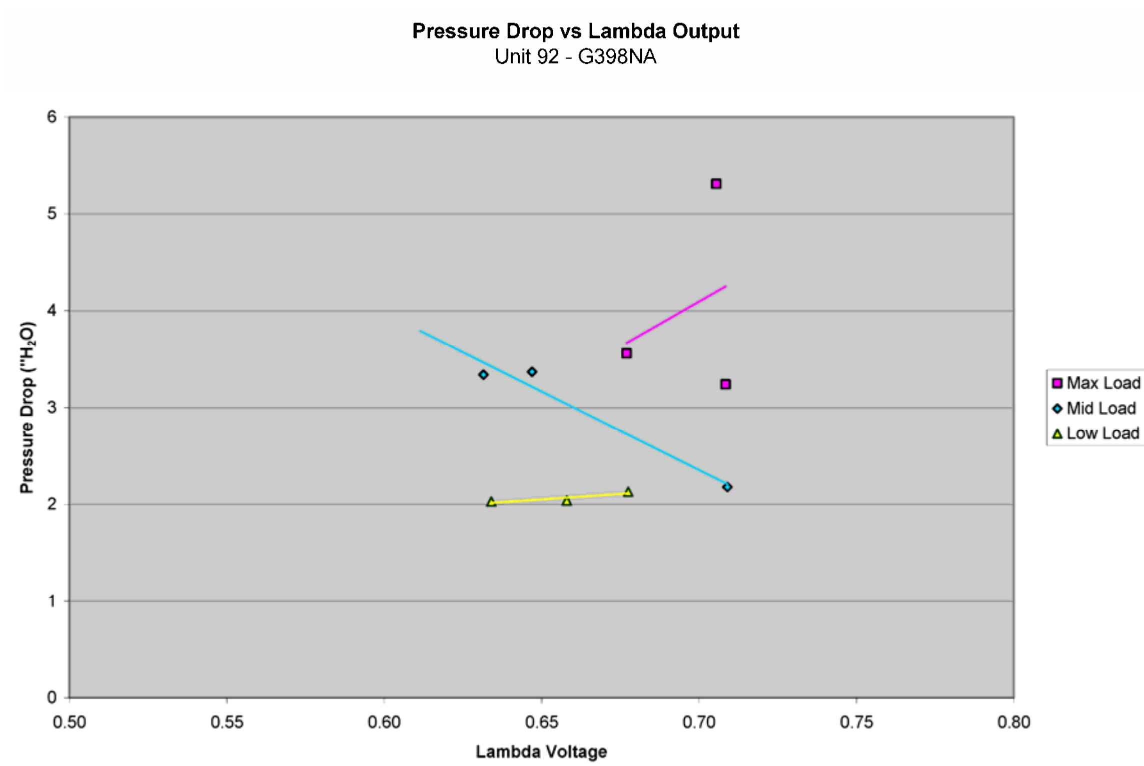

Figure 20: Pressure drop versus engine load.

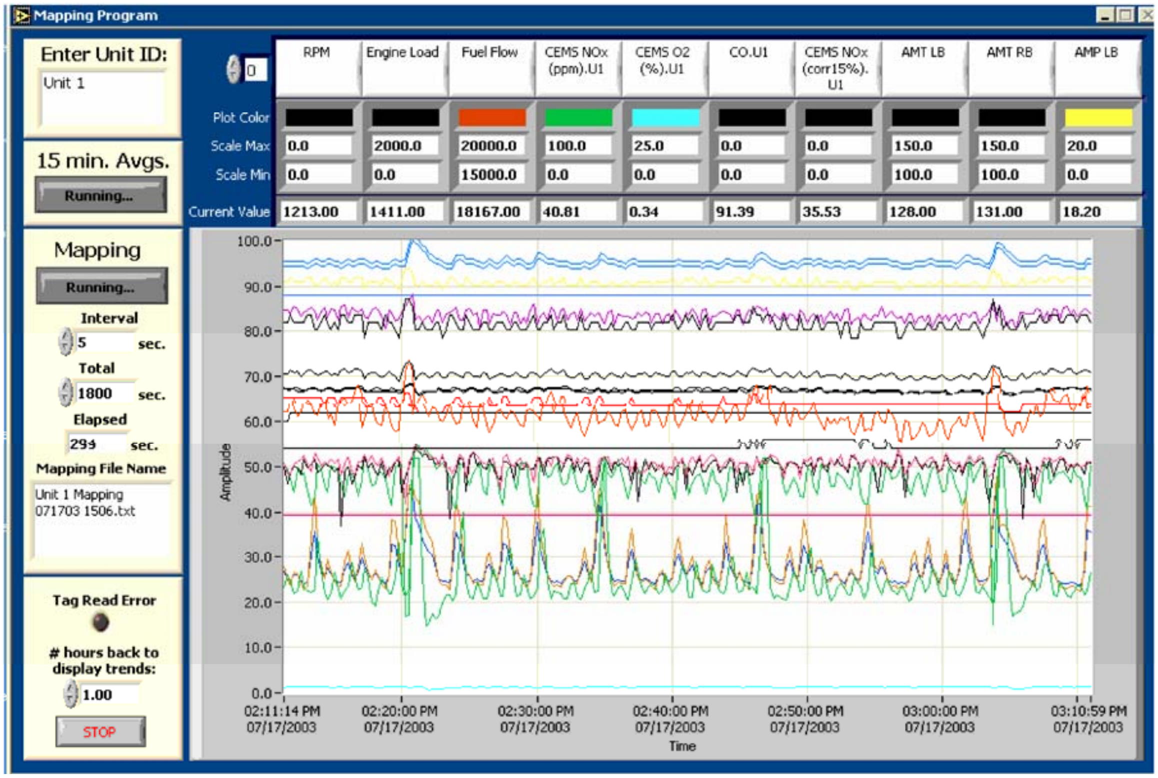

Figure 21: Real time trend of typical steady state operation.

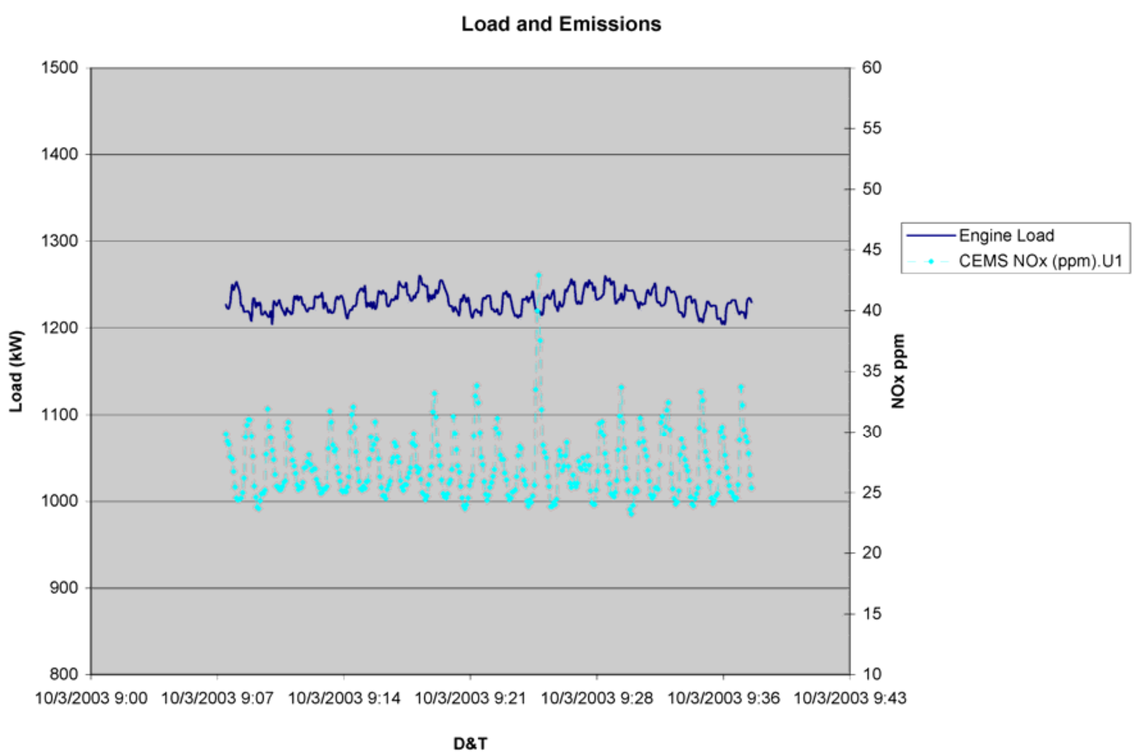

Figure 22: Typical system performance, which shows periodic fluctuation in engine load and NO_X with a period of ~1 minute.

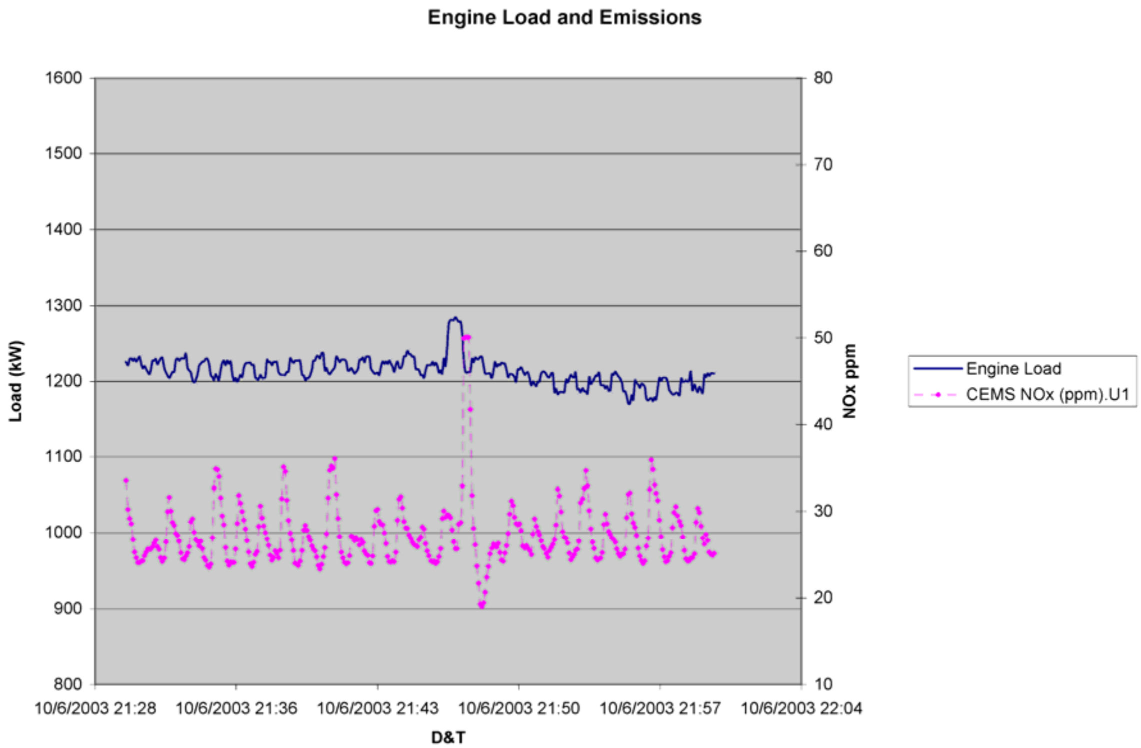

Figure 23: Typical engine load transient, which shows the step-up in load at ~21:46 with the brief NOX excursion immediately afterward and followed by NO_X undershot.

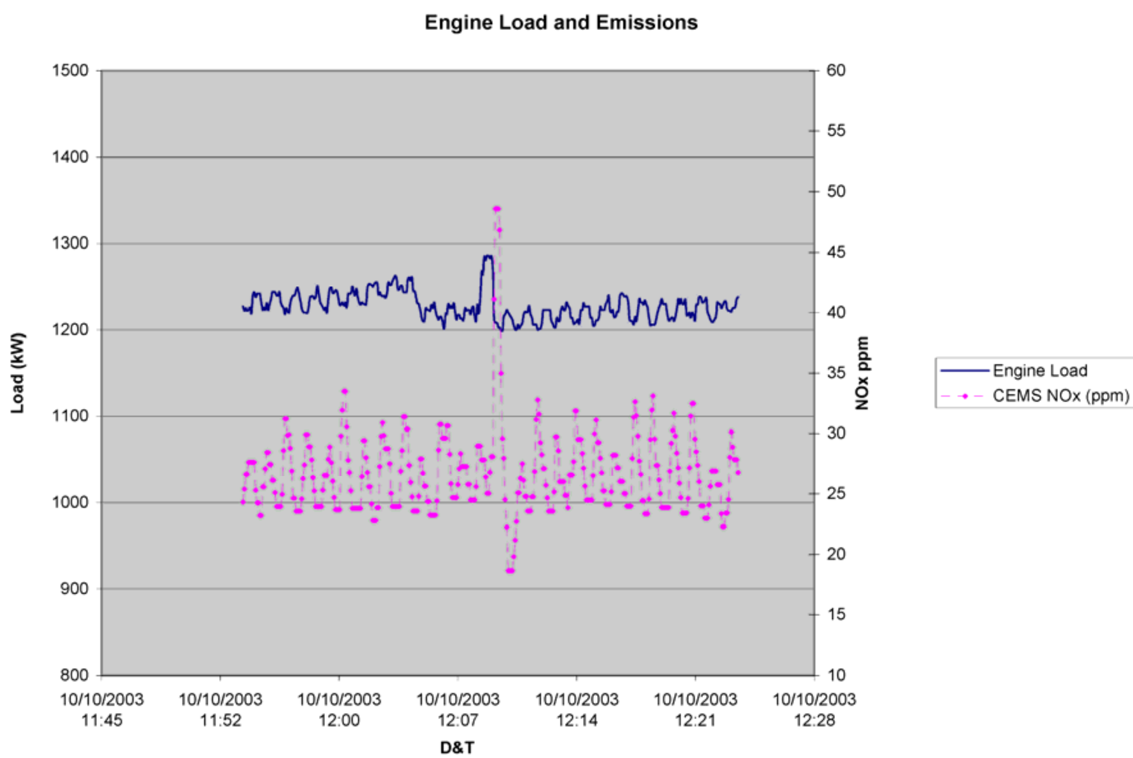

Figure 24: Engine load transient that shows the typical step-up at 12:09, but is preceded by a step-down at 12:04, which did not create an excursion.

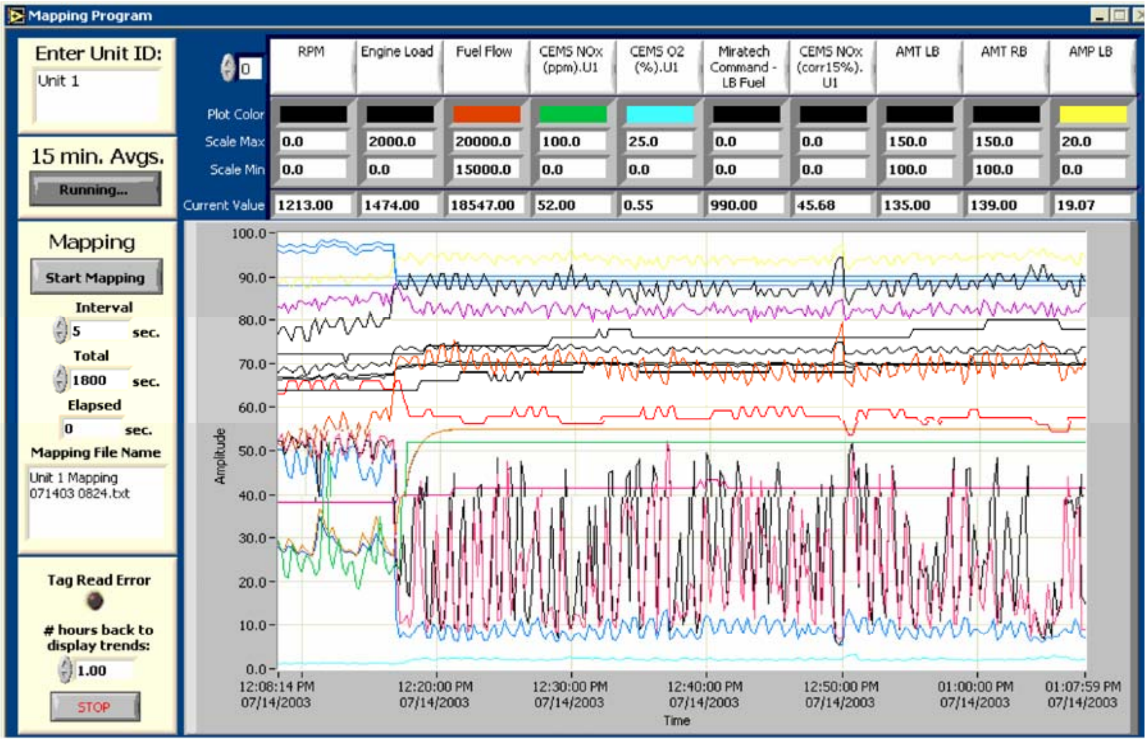

Figure 25: Typical out-of-control operation.

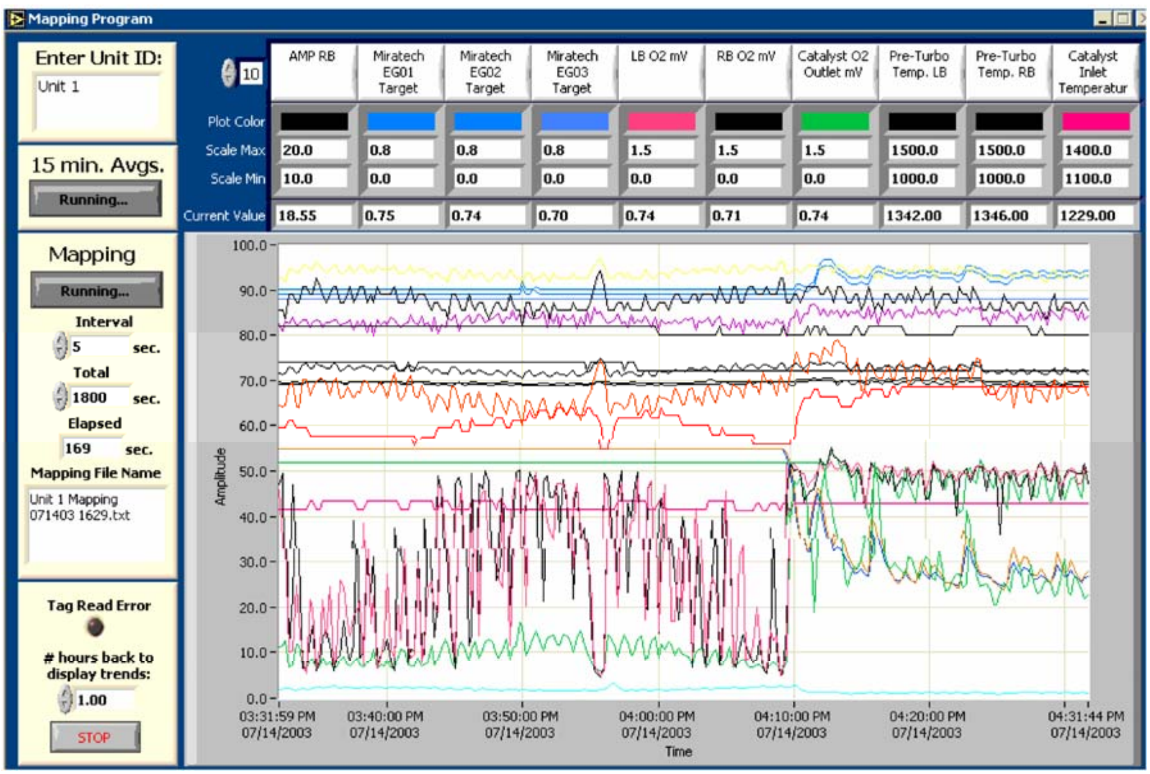

Figure 26: Data recorded several hours later than Figure 25, which shows the restoration of supplemental fuel valve control at 4:10 pm with NO_X and O_2 immediately returning to normal values.

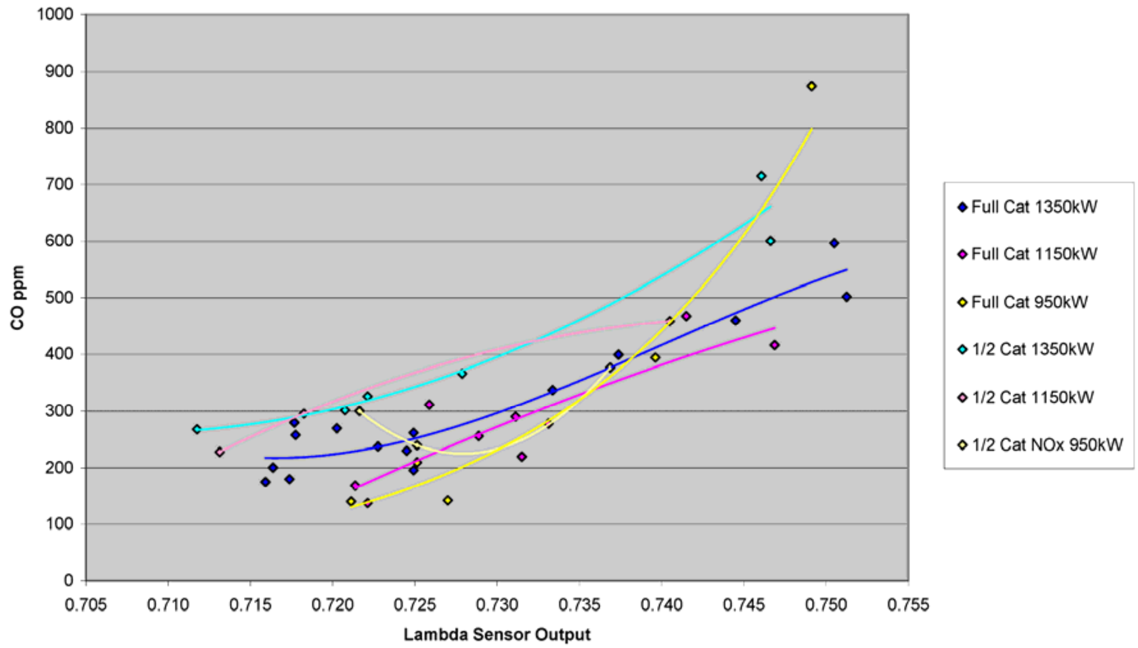

Figure 27: Comparison of CO concentration versus lambda sensor output for a Waukesha rich-burn engine-generator.

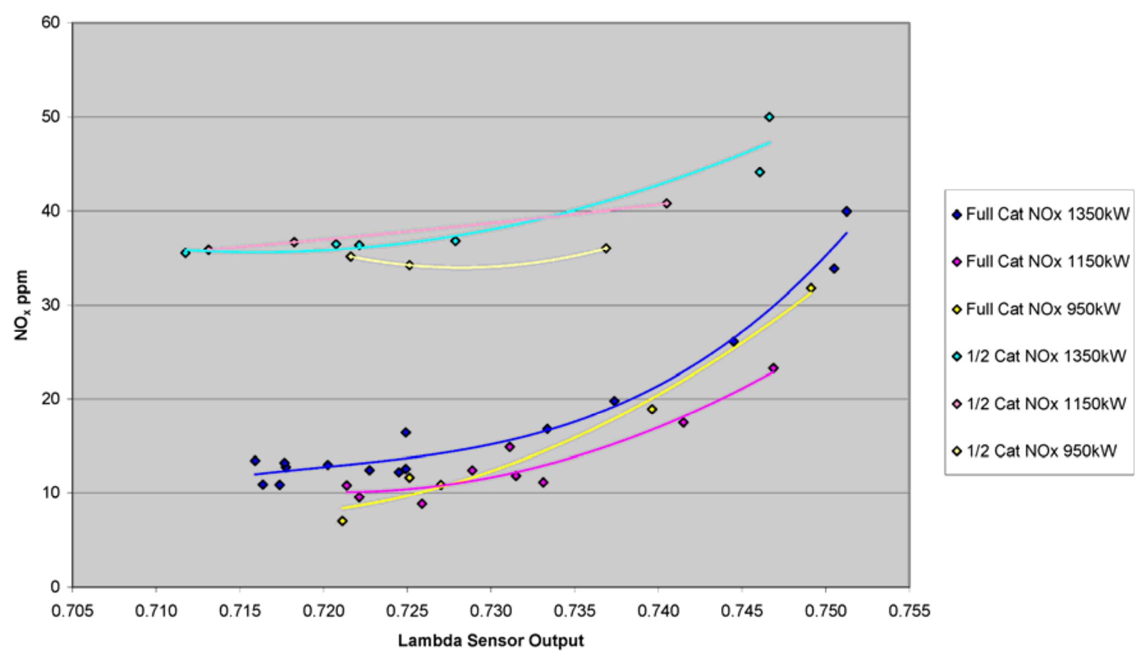

Figure 28: Comparison of NO_X concentration versus lambda sensor output for a Waukesha rich-burn engine-generator.

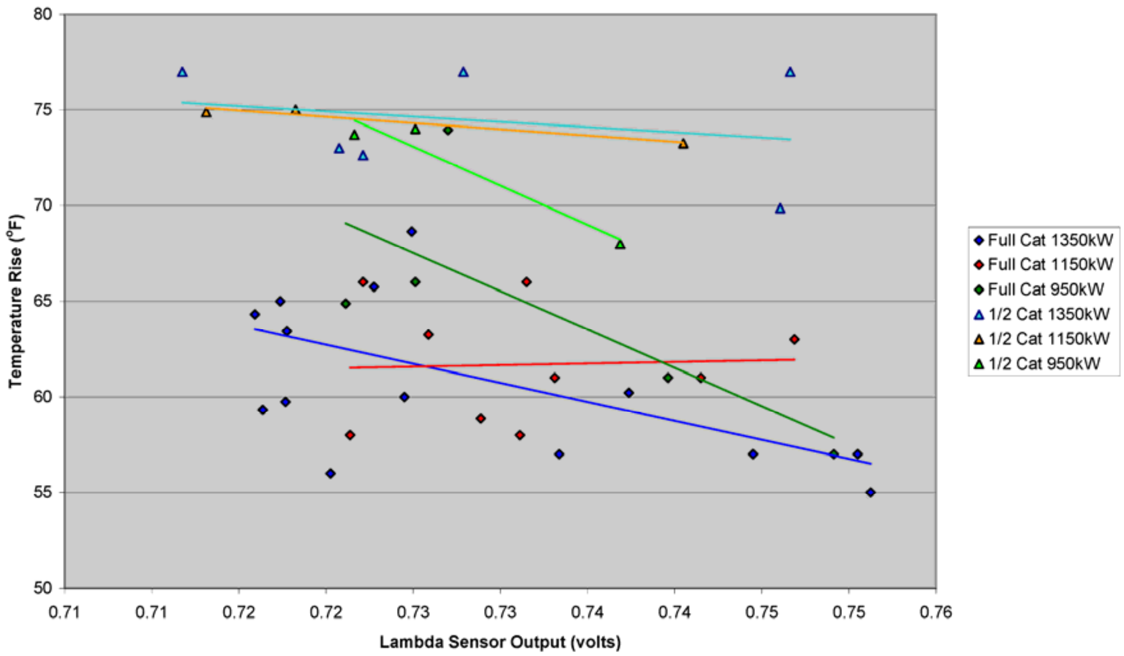

Figure 29: Comparison of temperature rise across the catalyst for a Waukesha rich-burn engine-generator.