
Sulfur-Resistant NOx Sorbate Catalyst for Increasing Longevity in Diesel Exhaust

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ABSTRACT

Sorbate or "trap" catalysts are capable of obtaining greater than 90% NOx conversion in lean exhaust over a wide range of operating temperatures. The critical limitation to sorbate catalysts is their susceptibility to sulfur poisoning, which is of particular concern in diesel applications where high sulfur levels exist and exhaust temperatures are typically too low for sulfur removal with thermal techniques. A novel catalyst formulation that exhibits sulfur-resistant characteristics is introduced here. The catalyst sorbs NOx and SO₂. The NOx is reduced and released as N₂, and the sorbed SO₂ in the form of sulfates and sulfites is reduced and released as H₂S and SO₂. The catalyst also oxidizes hydrocarbons and CO. The catalyst system incorporates a dual-chamber design for efficient operation. H₂, available from onboard fuel reformers, is used as the reductant.¹ The catalyst exhibits two beneficial characteristics related to sulfur: the NOx conversion decay rate due to sulfur-poisoning is reduced relative to standard NOx sorbate catalysts, and the sulfur-poisoned NOx sites can be cleansed of sulfur and reactivated by reduction at temperatures in the diesel exhaust range. This paper will show data from tests of the catalyst on a bench scale reactor and a stationary light-duty diesel engine. Studies were conducted with varying engine load, NOx level, and exhaust temperature. All testing was performed under steady-state conditions with No. 2 Diesel.

INTRODUCTION

Sulfur compounds in exhaust have negative effects on the exhaust system of an internal combustion engine. The performance of many aftertreatment devices, such as catalysts, degrades with increased exposure to sulfur compounds in a phenomenon known as "sulfur poisoning". In addition, sulfur compounds in the exhaust gas recirculation (EGR) stream cause excess wear on the engine and EGR components due to the acidic nature of sulfur compounds.

The effects of sulfur on aftertreatment devices and EGR components makes reducing emissions from diesel engines difficult, but upcoming regulations will require reduced emissions. One specific aftertreatment technology that has exemplified the problems associated with reducing emissions in sulfur containing streams is the NOx sorbate, or "trap", catalyst. NOx sorbate catalysts have shown excellent NOx reduction performance (>90%) in lean exhaust streams, but sulfur poisoning dramatically reduces the catalyst's active lifetime.^{2,3} Although some techniques exist for removing sulfur from NOx sorbate catalysts, high exhaust temperatures are required for the sulfur removal.⁴ The high temperatures used are above the range of most diesel exhaust and may cause sintering of precious metal components on the catalyst.

Removing the sulfur from diesel during the refining process is an option for reducing harmful effects of sulfur; however, the additional refining necessary would likely delay long-term fuel availability and increase fuel costs. Even if the sulfur level in fuel could be reduced to near-zero levels, contributions of sulfur to the exhaust stream from lubricants would still cause significant levels of sulfur compounds in the exhaust, and in the removal of sulfur from lubricants, the lubrication properties of oil can be reduced. Thus, a "sulfur-free" combustion system is unlikely.

One demonstrated method to reducing effects of sulfur in diesel is to remove sulfur compounds from the exhaust with a sulfur catalyst.^{5,6} The sulfur catalyst protects downstream devices from the harmful effects of sulfur. Although the technique has reduced the amount of sulfur interacting with a downstream NOx sorbate catalyst, the complete elimination of sulfur from the exhaust is not probable; some slip of SO₂ through the sulfur catalyst will most likely occur. Thus, similar to reducing the sulfur content in fuel, the protection provided by a sulfur catalyst will only reduce the degradation due to sulfur. Using diesel with reduced sulfur content in conjunction with the sulfur catalyst protection can further increase

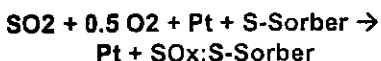
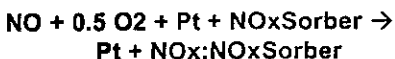
catalyst durability; however, reaching target catalyst lifetimes of 150,000-200,000 miles economically will still be challenging.

Recently an advancement in sorbate catalyst technology has occurred that shows promise as a technology that can reduce and potentially eliminate permanent sulfur poisoning of a NOx sorbate catalyst. A new NOx sorbate catalyst formulation that is capable of storing and releasing sulfur compounds is introduced here.⁷ The sorbate catalyst sorbs NOx and SO₂, and reduces and releases the sorbed species as N₂ and H₂S, respectively. The NOx conversion performance of the catalyst decays at a slower rate than standard NOx sorbate catalyst formulations, and the sulfur sorbed by the catalyst is released by the catalyst during reduction at exhaust temperatures well within the typical range of the diesel exhaust. This paper will show data from tests of the catalyst on a bench scale reactor and on diesel engine exhaust. The catalyst, as used in the system, offers the added benefit of removing sulfur from the exhaust for EGR use.

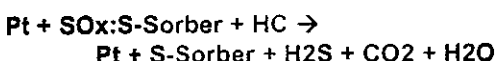
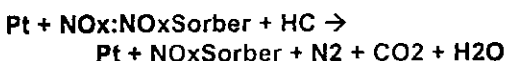
SULFUR-RESISTANT NOx CATALYST

The sulfur-resistant NOx catalyst (NOx/SOx catalyst) sites are active with NOx, SO₂, CO, and hydrocarbons. The NOx/SOx catalyst is a Pt-based sorbate, or "trap", catalyst. All of the tests in this paper were completed with the NOx/SOx catalyst applied to a corderite catalyst substrate (230/in² cell density). Space velocities of 22,500/hr and 23,000/hr were used for the bench scale and engine experiments, respectively. The NOx/SOx catalyst sorbs NOx and SO₂ in a lean exhaust stream; NO is oxidized to NO₂ on the catalyst surface prior to sorption. The SO₂ is sorbed as SO₃. The NOx/SOx catalyst also oxidizes CO and hydrocarbons; however, the study presented here will only focus on NOx and sulfur control.

The chemical reactions involving sorption of NOx and SO₂ on the catalyst are given below (the sorber components are proprietary). The reactions occur on the same catalyst.



The chemical reactions involving regeneration or reduction of the catalyst are:



During the NOx and SO₂ sorption process, catalyst sites become filled, and sorption of NOx and SO₂ begin to decrease. After saturation of the NOx/SOx catalyst sites

occurs, the sorbed species on the catalyst are released during a process called regeneration. During regeneration, a low flow of net-reducing gas is passed over the catalyst surface. H₂, CO, and hydrocarbons (including diesel) are suitable reductants. The reductant in the regeneration gas reduces and releases the sorbed NOx as N₂. The sorbed sulfur in the form of sulfates and sulfites is released as SO₂ and can be reduced to H₂S. The ratio of H₂S to SO₂ depends on many parameters, but in general the majority of sulfur is released as H₂S. An oxidation catalyst will be required downstream of the catalyst system to convert the H₂S to SO₂.

The NOx/SOx catalyst sorbs NOx and SO₂ independently, but present theories suggests that the sorption of NOx and SO₂ are closely coupled on a nanometer scale for the majority of catalyst sites. Thus, the sorption of SO₂ by the SO₂ sorbate prevents sorption of SO₂ on the NOx sorbate, which is in essence sulfur poisoning. In addition, the intimate mixture of precious metal with the NOx and SO₂ sorbates aids in the release of sulfur from the NOx sorbate site when sulfur poisoning occurs.

Three theories for the ability of the NOx site to be cleansed from sulfur poisoning exist. One theory is that the molecular bond strength of the sulfur compound to the NOx sorbate is decreased which aids release of the sulfur at a lower temperature range. A second theory is that the sulfur compound migrates away from the NOx sorbate during regeneration. Finally, the sorbed sulfur species on the sulfur site may not directly bond to the NOx site, but the presence of the sulfur on the precious metal site may "mask" sorption of NOx or sulfur to the NOx site.

The path of sulfur on the catalyst site is a function of temperature. At temperatures below 250°C, the capture of SO₂ on the catalyst site occurs, but release of the sulfur is suppressed with a smaller number of catalyst sites releasing sulfur during regeneration. At temperatures greater than 250°C the number of catalyst sites releasing sulfur during regeneration increases with temperature to approximately 440°C where nearly all active sites will release sorbed sulfur.

The sorption and reduction of NOx by the NOx/SOx catalyst occurs efficiently over a broad range of temperature. A decrease in the capacity for NOx sorption can occur due to sulfur poisoning, but the rate in the decrease is less than observed with a standard NOx catalyst. When sulfur poisoning of the NOx sorption occurs, the site can be reactivated for NOx sorption during the regeneration process. The temperatures at which reactivation, or sulfur cleansing, of the NOx sorption site occurs are closely related to the temperature profile for sulfur release from the sulfur sorption sites. Thus, reactivation of the NOx sites begins at 250°C, and full reactivation of NOx sites occurs at approximately 440°C.

BENCH REACTOR RESULTS

An experiment characterizing the behavior of the NO_x/SO_x catalyst was performed on a bench scale reactor with simulated exhaust. The experiment consisted of five (5) runs that included sorption and regeneration stages. The runs will be referred to as runs A, B, C, D, and E; alphabetical order matches chronological order.

Standard analyzers were used to collect the data. The sorption and regeneration space velocities were 22,500/hr and 3,500/hr, respectively. The typical operating temperature was 360°C. The sorption gas consisted of 100 ppm NO, 50 ppm CO, 3.05% CO₂, 14.5% O₂, and 10.2% H₂O in a N₂ carrier. The regeneration gas consisted of 4.0% H₂, 200 ppm CO, 1.0% CO₂, and 38.8% H₂O in a N₂ carrier. During run B, 100 ppm of SO₂ was included in the sorption gas to purposely poison the catalyst. Also, the regeneration temperature was increased to 442°C during run D. Catalyst inlet temperatures and data from the runs are summarized in Table 1.

Figure 1 shows the NO_x performance of the catalyst during the sorption stages of the runs. A represents the baseline data for the experiment. During run B sulfur poisoning of the catalyst occurred, and the capacity for sorbing NO_x decreased. Runs C and D were completed under the same conditions as run A and show the decreased activity due to sulfur poisoning. Regeneration of the catalyst was performed at 363°C after run C, but after run D, the catalyst was regenerated at 443°C. Near full recovery of NO_x sorption capacity was obtained in run E after sulfur release during the regeneration at 443°C (see Figure 2).

Fig. 2 shows the sulfur release during regeneration for the runs. Note that the regeneration exhaust gas was diluted with air to supply the analyzers with sufficient flow. Also, prior to reaching the analyzers, the gas passed through a converter to convert H₂S to SO₂ for detection by the SO₂ analyzer. Run B shows that some sulfur was released by the catalyst during regeneration at 363°C, and during sorption in run C the NO_x capacity did improve some (see Table 1). A larger amount of sulfur was released at higher temperatures in run D. The total amount of sulfur released from the catalyst was not equivalent to the amount added to the catalyst; however, the data in run D indicates that more sulfur would be released with added regeneration time. The unaccounted sulfur mass may be present on the catalyst surface or released as an undetectable form of sulfur. Further analysis will be required to determine a mass balance.

ENGINE TEST DESIGN

The diesel aftertreatment system was tested on a light-duty platform. A 3.9-liter turbo-assisted diesel engine (Cummins 4B3.9T) produced the exhaust for testing. No

particulate control or other exhaust treatment was used. The engine was attached to a generator as a gen-set, and load was applied to the engine with a resistive load bank. The engine speed was held constant at 1800 rpm. The exhaust temperature and NO_x level varied with engine load. All testing was performed with steady-state operation of the engine.

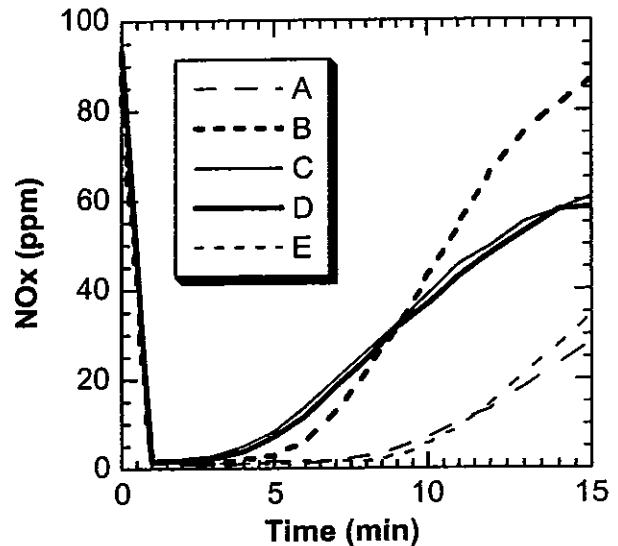


Figure 1. Data obtained on a bench scale reactor showing the regeneration of sulfur poisoned NO_x sites.

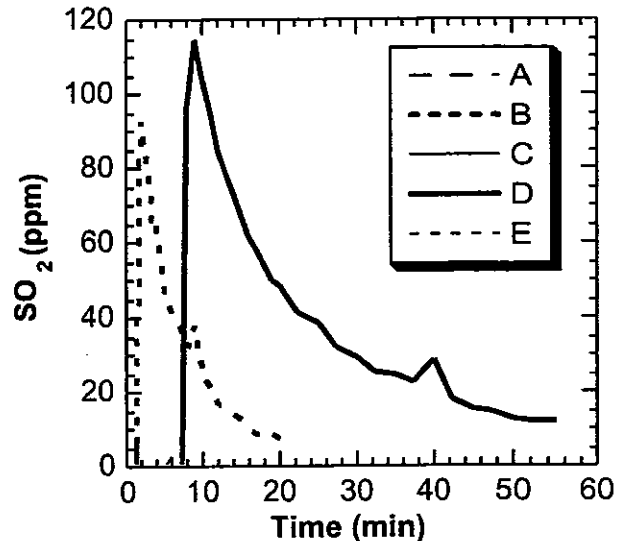


Figure 2. Data obtained on a bench scale reactor showing the release of sulfur during regeneration.

Table 1. Mass table summarizing the sorption and release of sulfur. The NO_x capacity of the catalyst corresponds to the sulfur level on the catalyst. Sulfur release during regeneration is a function of temperature. All temperatures shown are catalyst inlet temperatures. Regeneration temperatures differed from sorption temperatures due to space velocity differences (furnace temperature was constant). NO_x mass is as NO₂.

Run	Sorption			Regeneration	
	Temperature (C)	S Added (mg)	NO _x Sorbed (mg)	Temperature (C)	S Released (mg)
A	291	0.0	29.8	363	0.0
B	292	22.3	21.8	363	3.6
C	292	0.0	23.3	363	0.0
D	293	0.0	23.7	442	12.4
E	294	0.0	29.5	364	0.0
Total	---	22.3	---	---	16.0

The catalyst was used in a dual-chamber system (see Figure 3) described in earlier work.⁶ Each chamber of the system contained a catalyst volume of 9.8 L (23,000/hr space velocity and 230/in² cell density). Valves controlled the flow of the main engine exhaust and the regeneration gas through the catalyst chambers. In the work presented here, the flow of regeneration gas was in a reverse direction relative to the main exhaust flow; a bypass line mixed the regeneration gas exhaust with the main exhaust downstream of the catalyst system. The reverse flow arrangement is not necessary and was used since previous work utilized the arrangement.

Cycle periods and thereby regeneration frequency were held constant at 2.5 minutes. To reduce system size by increasing space velocity, reduced cycle times will be required. Frequency of regeneration could potentially be controlled by a downstream NO_x sensor or by an engine map-based control scheme. These more advanced control schemes may be required for fuel penalty minimization and increased response control suitable for transient engine conditions.

The engine used No. 2 Diesel for all tests. The sulfur level in the fuel was 389 ppm; SO₂ levels in the exhaust were typically 12 to 30 ppm. Typical NO_x levels ranged from 150 to 2400 ppm. CO levels were typically 100 to 800 ppm.

Although diesel fuel can be used as the reductant, the data presented here was obtained with a simulated reformer gas (H₂ reductant). Regeneration required low carrier flow; the space velocity was 1,500/hr. The simulated reformer gas used for regeneration was 8% H₂ in a N₂ carrier.

Exhaust gases were analyzed at standard conditions. Non-dispersive infrared analyzers were used for NO_x detection. SO₂ was measured with non-dispersive ultraviolet detection. All gases passed through a filter and chiller to remove the particulate matter and H₂O from the exhaust, respectively. One set of analyzers was used

to test engine out and catalyst out exhaust. NO_x conversions shown were computed with the most recent engine out NO_x measurement.

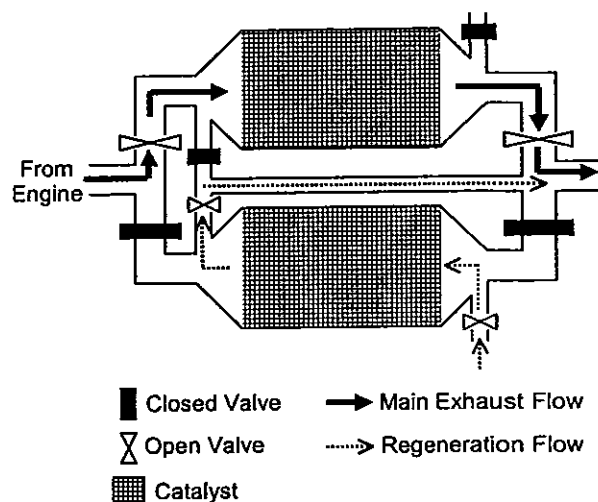


Figure 3. Diagram showing the catalyst system used for engine testing. Each chamber of the dual-chamber device contained a catalyst. The exhaust flow from the engine was cycled between the chambers. The top catalyst chamber is shown treating the exhaust from the engine. The bottom chamber is shown with the net-reducing gas regenerating the catalyst.

ENGINE TEST RESULTS

SULFUR SORPTION AND RELEASE – Figure 4 shows the NO_x conversion and SO₂ out obtained by the system at a low load and temperature point. The NO_x inlet level to the catalyst was 372 ppm; the exhaust temperature was 180 °C. A plot showing the NO_x conversion of a standard NO_x sorbate catalyst is shown for comparison. Over the 2 hour time frame NO_x conversion does not

vary significantly for the data, but the NOx conversion of the standard NOx sorbate catalyst decreases with time due to sulfur poisoning. Note that no system out SO₂ was detected indicating that the SO₂ is being sorbed on the catalyst. The ability of the catalyst to remove SO₂ from the exhaust stream creates potential for use in the EGR loop especially at low loads where EGR rates are high.

Figure 5 shows the SO₂ concentration and exhaust temperature measured during the collection of the data shown in Fig. 4 and for a 1 hour period immediately following the data shown in Fig. 4. The engine load was raised to 50 kW at a time of 120 minutes, and the exhaust temperature raised accordingly. NOx conversion was not determined for the transient period shown since only system out exhaust was sampled. The results demonstrate the release of sulfur from the catalyst as a function of temperature. As the temperature rose above 250°C the sulfur began to be released. The sulfur was released in peaks indicating that the release of sulfur is due to reduction. Only SO₂ release is shown; H₂S release occurred but was not measured. After steady-state operation began, the magnitude of the SO₂ peaks became constant, and the SO₂ continued to be released since an inlet level of 28 ppm SO₂ was still being sorbed, and released, by the catalyst during steady-state operation.

PULSE-SULFUR POISONING AND RECOVERY – The slow NOx conversion decay rate of the NOx/SOx catalyst combined with the ability of the NOx/SOx catalyst to release sulfur at medium and high load points made sulfur poisoning of the NOx/SOx catalyst difficult. To test the capability of the NOx/SOx catalyst to recover from sulfur poisoning, an experiment was conducted where an extra pulse of SO₂ was injected into the exhaust stream

to purposely poison the NOx/SOx catalyst. The test procedure is as follows. At a low engine load (10 kW) and temperature (180°C) NOx conversion was monitored to provide baseline data. Steady-state operation at the low load point continued for 80 minutes, and a second NOx conversion was measured at the 80-minute time mark. Then, the catalysts were poisoned with an excessive injection of SO₂ into the exhaust; the post-poisoned NOx conversion was measured. After poisoning, a brief excursion to high load (50 kW) operation was conducted to raise the temperature of the catalyst to 372°C where the sulfur was released. Then,

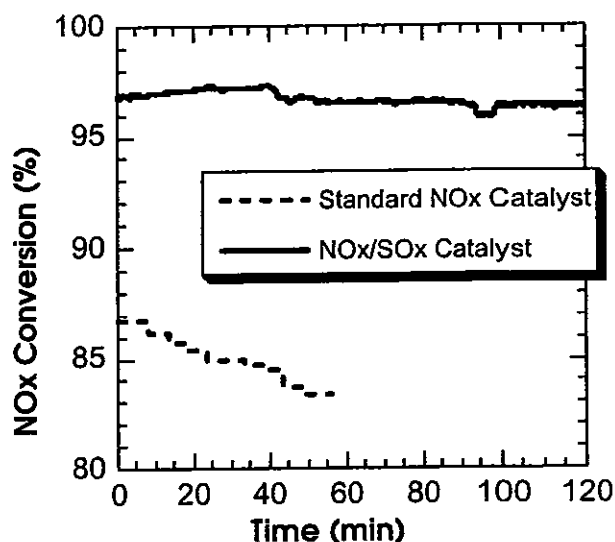


Figure 4. Data showing difference in rate of NOx conversion decay for low temperature operation of NOx/SOx catalyst vs. a standard NOx sorbate catalyst.

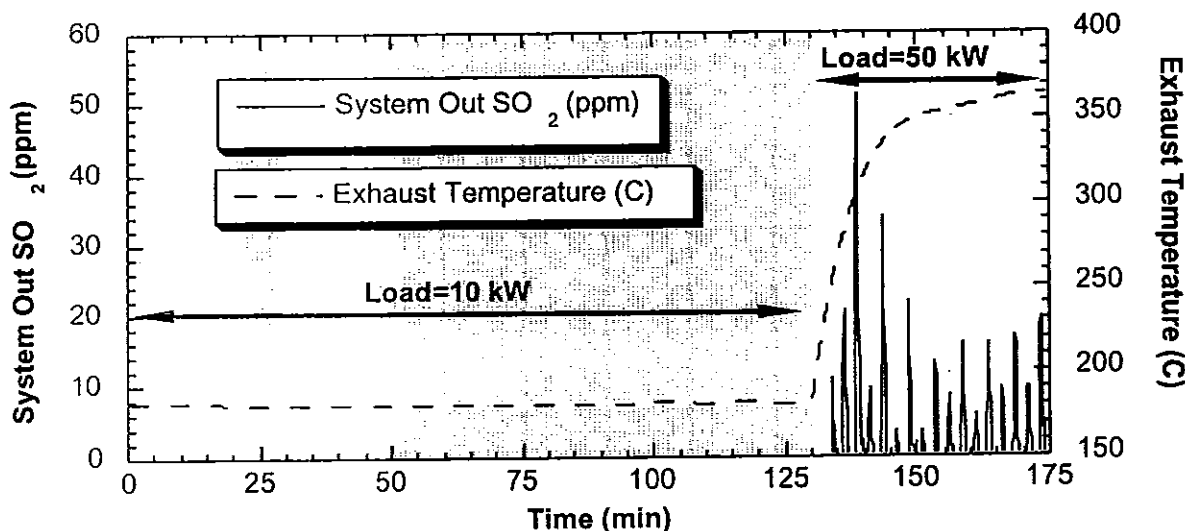


Figure 5. Evidence of the release of sulfur compounds during regeneration when the catalyst temperature rises above 250°C.

steady-state operation at the low load point was revisited, and the NO_x conversion after the sulfur regeneration at high load was measured.

The sulfur poisoning was performed with the injection of a high rate of SO₂ into the exhaust manifold. Two injections were made to purposely poison the catalyst in each chamber of the system. Figure 6 shows the SO₂ level in the exhaust measured immediately upstream of the catalyst system. Two peaks are shown; the volume of each peak represents the extra SO₂ added to one catalyst in a 2.5 minute time frame. The mass of sulfur added to the catalysts in chambers 1 and 2 were 30.6 g and 21.2 g, respectively. The average mass of the sulfur additions (25.9 g) represent approximately 50 hours of operation at low load with 500 ppm in sulfur fuel as calculated with fuel consumption. Based on the volume of catalyst, the SO₂ loading of the catalysts were 3.1 g/L and 2.2 g/L, respectively.

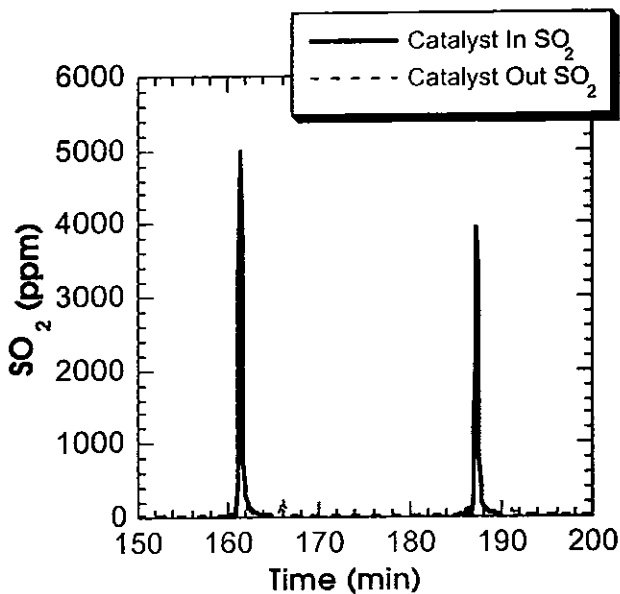


Figure 6. Catalyst inlet SO₂ concentration showing two sharp SO₂ peaks. The SO₂ peaks are the result of SO₂ injected into the exhaust manifold. Two pulse injections were made in order to purposely sulfur poison the catalysts in both chambers of the test system.

Figure 7 shows system out NO_x obtained at different stages in the experiment. In addition, the NO_x conversion and inlet NO_x level are shown for each 10-minute plot in the figure. The baseline performance was 93.6% NO_x conversion at a 233 ppm NO_x inlet level. After 80 minutes of operation at the low load point, NO_x conversion decreased slightly to 92.8% with an inlet NO_x concentration of 233 ppm. After the extra sulfur poisoning with SO₂ injection occurred, the NO_x conversion decreased to 75.8% at an inlet NO_x level of 239 ppm; the reduced performance of the catalyst is evident in the profile of the system out NO_x plot. After

the excursion to high load for sulfur release, the NO_x conversion measured was 93.4% at a NO_x inlet level of 261 ppm. Thus, within experimental error, the catalyst recovered all NO_x conversion performance with the regeneration at high load operation.

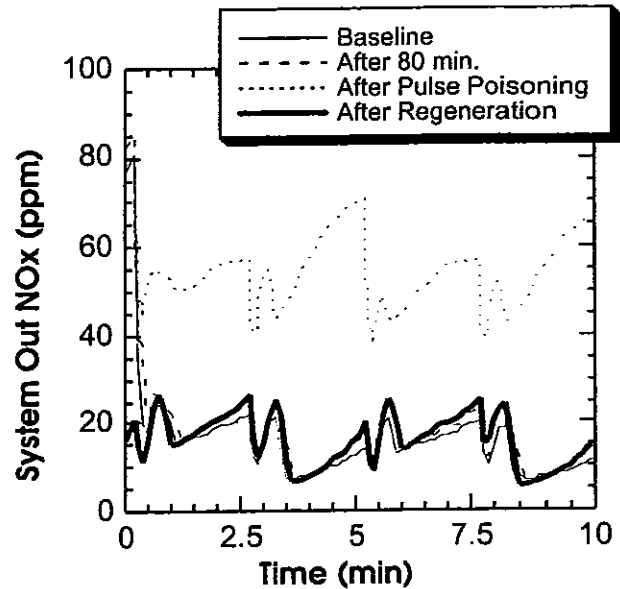


Figure 7. Comparison of NO_x conversion at four different times in the SO₂ pulse poisoning experiment. The baseline data is the original NO_x conversion. After 80 minutes of operation at low load, the NO_x conversion was measured again and was slightly less. After the addition of SO₂ in the form of two massive pulse injections (Fig. 5), the NO_x conversion decreased dramatically. Finally, after operation at high load (exhaust temperatures of 350°C) and return to low load conditions, the NO_x conversion performance of the catalyst was recovered.

CYCLIC OPERATION FOR CATALYST CLEANSING – The occasional operation with high exhaust temperatures is expected to cleanse the NO_x/SO_x catalyst of any sulfur poisoning that has occurred at lower exhaust temperatures. Figure 8 shows the performance of the NO_x/SO_x catalyst in cyclic operation between medium and high load points; engine load, engine out NO_x level, exhaust temperature, and NO_x conversion are shown. After a three hour warm up period conducted with a sweep of engine loads, two-mode steady-state operation was implemented with 50 kW and 30 kW load points. During operation at 50 kW load, the NO_x conversion did drop below 70%; the drop was due to the higher inlet NO_x levels (>2000 ppm) which caused early catalyst saturation. The catalyst saturation could have been avoided by using a shorter cycle interval for the catalyst system, but the 2.5-minute cycle time was held constant for this experiment.

During the operation at 30 kW load points, slight decreases in NOx conversion were observed; however, the operation at higher temperatures at the 50 kW load points regained any lost NOx conversion performance. No permanent loss in NOx conversion performance was observed over the 11 hour experiment.

CONCLUSION

- A sorbate catalyst with the ability to sorb NOx and SO₂ in has been demonstrated in diesel exhaust on a light-duty platform with No. 2 Diesel fuel.
- The NOx/SOx catalyst demonstrated the ability to sorb SO₂ and release the SO₂ primarily as H₂S during the regeneration process; sulfur release occurred at temperatures as low as 250°C.
- The NOx/SOx catalyst decay rate in NOx conversion due to sulfur poisoning is less than the decay rate associated with standard NOx sorbate catalysts.
- After sulfur poisoning, the NOx/SOx catalyst can be cleansed of sulfur during regeneration at temperatures well within the diesel exhaust range. Results showed that NOx conversion performance lost in sulfur poisoning can be regained by the regeneration process.
- Further testing of the NOx/SOx catalyst will be required to confirm that no permanent degradation of catalyst performance is occurring due to sulfur effects.

ACKNOWLEDGMENTS

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REFERENCES

1. A. Rabinovich, L. Bromberg, D. R. Cohn, J. Surma, and J. W. Virden, "Onboard Plasmatron Reforming of Biofuels, Gasoline and Diesel Fuel", SAE 981920 (1998).
2. H. Luders, P. Stommel, and S. Geckler, "Diesel Exhaust Aftertreatment – New Approaches to Ultra Low Emission Diesel Vehicles", SAE 1999-01-0108.
3. M. A. Dearth, J. S. Hepburn, E. Thanasiu, J. McKenzie, and G. S. Horne, "Sulfur Interaction with Lean NOx Traps: Laboratory and Engine Dynamometer Studies", SAE 982595 (1998).
4. M. Guyon, F. Blejean, C. Bert, and Ph. Le Faou, "Impact of Sulfur on NOx Trap Catalyst Activity – Study of the Regeneration Conditions", SAE 982607 (1998).
5. J. E. Parks II, G. J. Wagner, W. S. Epling, M. W. Sanders, and L. E. Campbell, "Near-Zero NOx Control for Diesel Aftertreatment", SAE 1999-01-2890.
6. J. E. Parks II, G. J. Wagner, W. S. Epling, M. W. Sanders, and L. E. Campbell, "NOx Sorbate Catalyst System with Sulfur Catalyst Protection for the Aftertreatment of No. 2 Diesel Exhaust", SAE 1999-01-3557.
7. US Patents 5451558, 5599758, 5607650, 5650127, 5665321, and 5762885.

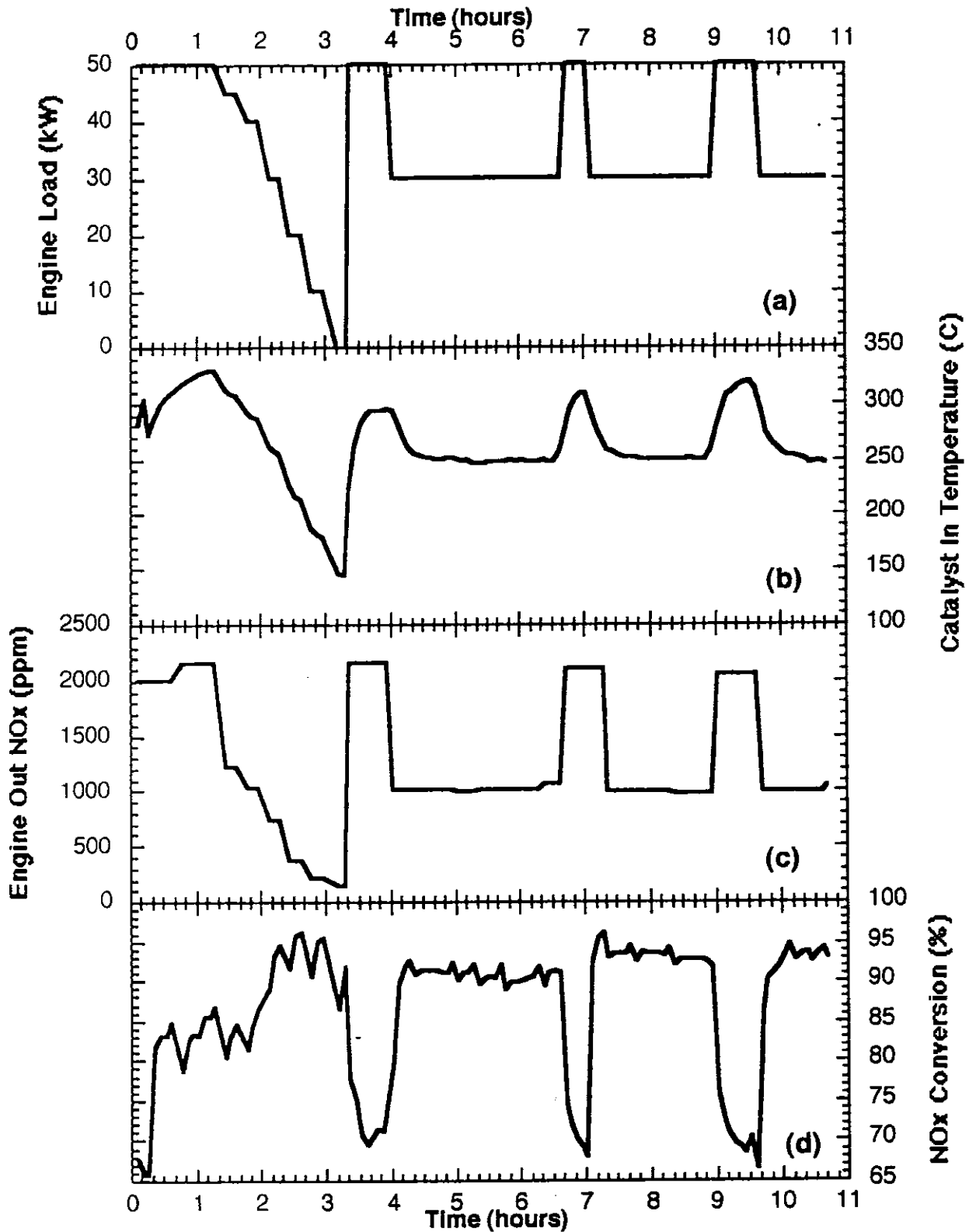


Figure 8. Data showing the effect of cyclic exhaust temperature on catalyst performance. Engine load (a), exhaust temperature (b), engine out NOx (c), and NOx conversion (d) are shown. Any NOx conversion lost at low load and temperature can be recovered during operation at high load and temperature.