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ACCELERATED AGING USING FOCAS®–A BURNER BASED SYSTEM SIMULATING AN ENGINE

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ABSTRACT–Accelerated aging of engine exhaust system components such as catalytic converters are traditionally performed using an engine/dynamometer test stand. SwRI®'s FOCAS® system reduces or eliminates many of the engine based aging limitations. This paper will describe several studies. These include: 1) replication of engine based catalyst aging cycles with added precision and dependability; 2) catalyst aging with and without lubricating oil effects; 3) effects of lubricant phosphorus on catalyst performance; and 4) the potential to thermally age components beyond the capabilities of engine based systems. The first study includes the development of the SwRI FOCAS system to run programmed aging conditions with or without lubricating oil. A description of the subsystems is given. The second two studies used the SwRI FOCAS system to age catalysts. One study compared thermal-only aging using of the SwRI FOCAS system with equivalent aging on a traditional engine/dynamometer test stand. The other study examined the effect on catalyst performance of two lubricating oils containing different levels of phosphorus, and compared the results to field data generated using the same oils in a fleet of vehicles.

KEY WORDS : FOCAS®, Catalyst, Converter, Aging, Thermal, Oil

1. INTRODUCTION

Engine exhaust system components must be tested to insure that they will meet efficiency and durability requirements. Traditionally, these tests are performed using vehicles or engine test stands. However, relatively simple tests can often become more complex because the use of engines requires many controls and subsystems that are not necessarily relevant to the testing needs. These complexities can also lead to poor test accuracy and precision due to the large number of variables involved. In some cases, it is desirable to evaluate engine exhaust system components using test procedures and apparatuses that are specifically designed to reproduce vehicle and engine-based results, but with more accuracy, precision, and reliability, and optionally with capabilities beyond those of a vehicle or engine test system.

SwRI has been continuously developing the FOCAS system for ten years. The system was conceived to provide an exhaust gas stream generated by the combustion of standard engine fuels, such as gasoline, without the need to use an engine. An early goal was to separate the fuel and lubricating oil consumption into two independently controlled parameters, thereby permitting the study of engine exhaust system components in real exhaust gas, with or without the effects of lubricants. The system is set up to provide sufficient exhaust gas flow to age full size catalytic converters. It is also designed to operate at catalyst inlet temperatures as high as 1000°C.

2. EXPERIMENTATION AND RESULTS

2.1. FOCAS System Design

The FOCAS system consists of five main subsystems; a gasoline-fueled burner capable of continuously operating at stoichiometric Air-to-Fuel Ratio (AFR), or over a range of predetermined AFRs, an oil injection subsystem to allow the introduction of oil in a controlled quantity at various locations within the exhaust, an air blower, a heat exchanger, and a computerized control system.

The steady flow burner apparatus was initially designed to simulate the exhaust flow from a typical four-cylinder engine under a variety of load conditions, allowing full sized passenger car catalytic converters to be aged. The AFR of the burner exhaust gas is controlled and adjusted through computer feedback control.

The oil injection system provides control over the amount of oil consumed as a function of time. In addition, the location of the oil injector can be used to affect the degree of combustion of the oil (from almost unburned to almost completely burned).

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The blower subsystem provides the air for the burner. The mass air flowrate is computer-controlled.

The heat exchanger is used to reduce the burner outlet temperature into the range desired for catalytic converter aging. It is also used to maintain the desired temperatures through feedback control.

The computer control subsystem controls all of the burner operations. It can be remotely located away from the burner section for convenience.

Catalytic converter aging cycles, whether well known, client specific, or developed at SwRI, have been programmed into the FOCAS system and used to age catalytic converters over a wide range of conditions. Excellent aging cycle stability has been demonstrated relative to an engine. In comparison to an engine operating with several cylinders, the single-stage burner shows improved AFR control and stability, as well as improved exhaust flow rate stability. It has also been operated with catalytic converter inlet temperatures in excess of those achievable using a bench engine.

2.2. Thermal Aging Study

In the first of several studies(Sims and Sjohri, 1988), SwRI compared the results of FOCAS aging to that of a standard engine stand aging. The aging cycle used to perform this study was the General Motors Rapid Aging Test (Webb and Bykowski, 2003) version A (RAT-A). The aging cycle specifications are given in Table 1. The aging flowrate used 127 m^3hr^{-1} (75 SCFM), and aging was performed for 100 hours per catalyst. Six identical Ultra-Low emissions Vehicle (ULEV) catalysts were aged. Three were aged using the FOCAS system, and three were aged using the engine aging stand. The performances of the catalysts in a preconditioned state and aged, were determined using the EPA Federal Test Procedure (FTP), on a single ULEV-certified test vehicle (1998 Honda Accord, 2.3L, I-4, VTEC). A comparison of FTP performance degradation for the average engine- and FOCAS-aged catalysts is shown in Figure 1.

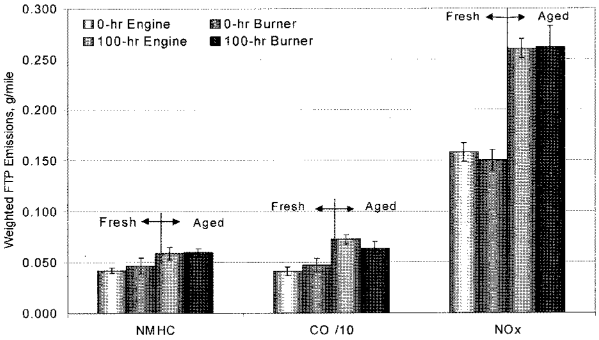

Figure 1. Comparison of average FTP performance degradation for the engine and FOCAS aged catalysts.

Both the engine- and FOCAS-aged catalysts exhibited comparable performance before and after aging. A statistical analysis of the data was performed using a repeated measured analysis of variance statistical model (Milliken and Johnson, 1992). Using a 95 percent confidence interval, there were no statistical differences between the aging methods and the FTP emissions results obtained.

2.3. Oil Poisoning Study

A number of studies have attempted to quantify the impact of oil components phosphorus, zinc, and calcium on catalyst performance (Drury and Whitehouse, 1994; Cully and McDonnell, 1995; Cully *et al.*, 1996; Ball *et al.*, 1997; Williamson *et al.*, 1984; Joy *et al.*, 1985). In the SwRI study (Webb, 2004), the objective was to develop and demonstrate a catalyst oil-poisoning aging and screening procedure to evaluate and differentiate the effect of oils with varying levels of phosphorus on catalyst performance.

First, an oil poisoning aging cycle was developed (since no such industry-based cycle existed). The cycle incorporates moderate aging temperatures, to prevent significant thermal aging effects, a cold-start portion, to simulate multiple vehicle cold starts, and an oil injection strategy. The cycle is called the MT-Aging Cycle. It consists of five operating modes, as described below.

2.3.1. Cold start

The first mode is intended to simulate vehicle cold-start. It was theorized that part of the oil poisoning of a catalyst might be attributable to a cold, raw oil mechanism. During cold-start, the engine and all exhaust components are cold. The engine is cranked, and some raw oil may be

Table 1. GM RAT-A aging cycle specifications.

	Description	Parameter specification	Mode Length, s
1	Closed-loop, stoichiometric	Inlet temperature = 800°C	40
2	Open-loop, fuel rich	3% CO to catalyst	6
3	Open-loop, fuel rich with air injection	3% CO, 3% O_2 to catalyst	10
4	Closed-loop, stoichiometric with air injection	Stoichiometric out of engine, continue air injection	4

emitted and deposited on the cold catalyst face. The catalyst becomes hot enough to be active shortly thereafter, but probably lights-off while the engine is still in an enrichment mode, which results in the raw oil on the catalyst surface coming up to catalyst operating temperature while the overall exhaust AFR is fuel rich (oxygen depleted). This creates a situation in which the oil on the catalyst face may reach temperatures sufficient to form ash, but there may not be enough oxygen present to fully oxidize the oil. The overall effect of the cold-start mechanism on catalyst degradation is not known, but it is believed that the effect may be a contributing factor to catalyst poisoning and should be included in the aging cycle. To achieve a 'cold-start', the catalyst is cooled to a bed temperature below 70°C, then with the burner off and the blower on; raw oil is injected for several seconds. The burner is then lit, and programmed into a fuel rich mode (13.75:1) while oil injection continued (for another 22 seconds), after which oil injection is halted and the enrichment mode is permitted to continue for another 60 seconds (to prevent excess build-up of unburned oil on the face of the catalyst).

2.3.2. Steady-State stoichiometric

During this mode, the burner is operated at a constant exhaust and oil flow, with the exhaust AFR perturbating (approximately ±0.2 AFR) about stoichiometric (fuel control is closed-loop on a UEGO sensor, but an EGO sensor is used to verify that the system is perturbating about stoichiometry). The intention of this mode is to simulate the bulk of normal vehicle operation and oil consumption, that is, fully warm operation at stoichiometric, with the oil being partially oxidized prior to entering the catalyst.

2.3.3. Mild thermal excursion

The mild thermal excursion mode is achieved by running the burner rich (AFR = 13.25:1) and injecting secondary air at the catalyst. Target catalyst bed temperature is 750-755°C for 10 seconds during the thermal excursion. The mild thermal component is incorporated to expose the oil deposit, as it is being formed, to a slightly elevated temperature. This would allow any compounds that require higher temperatures to form. In addition, the mild thermal aging would result in a higher catalyst surface temperature while the oil deposit is forming on the surface.

2.3.4. Steady-State lean

During the lean mode of operation, the burner is controlled to an AFR of 15.5:1. This lean excursion is incorporated to help oxidize any soot and remaining unburned oil, to prevent carbon build-up.

2.3.5. Cool-down

The burner is shut down during stoichiometric operation, and the cycle ended with a forced air cool down.

The MT aging cycle is one hour in length, and consisted of the following sequence of modes:

(1) Cold-start
(2) Rich warm-up
(3) Thermal excursion mode
(4) Steady-state stoichiometric mode
(5) Thermal excursion mode
(6) Repeat modes 4 and 5 five times
(7) Steady-state lean mode
(8) Steady-state stoichiometric mode
(9) Thermal excursion mode
(10) Steady-state stoichiometric mode
(11) Cool down

The targeted oil injection rate is 27 grams/hour, and oil is injected during all modes except for Mode 7, resulting in a consumption of about 28.7 cm^3 of oil per cycle. Figure 2 shows the measured catalyst bed temperature during one cycle of aging on the mild-thermal cycle. Figure 3 shows the measured exhaust (burner outlet) AFR profile for the same cycle.

Four equivalent catalysts were aged using the mild

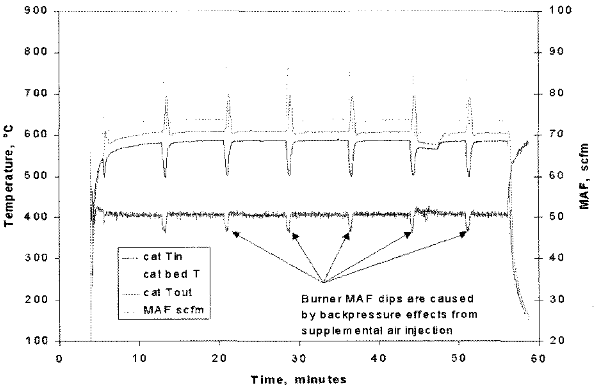

Figure 2. Catalyst bed and inlet temperatures during mild thermal aging cycle.

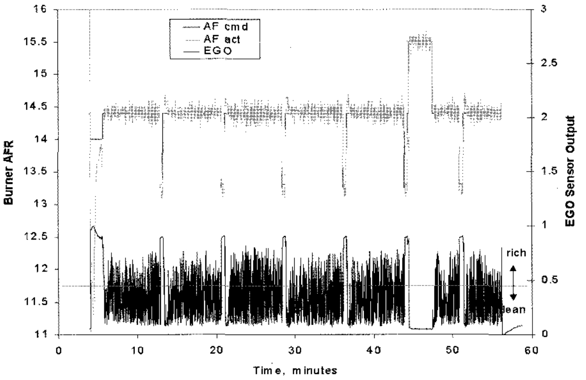

Figure 3. AFR during mild thermal aging cycle.

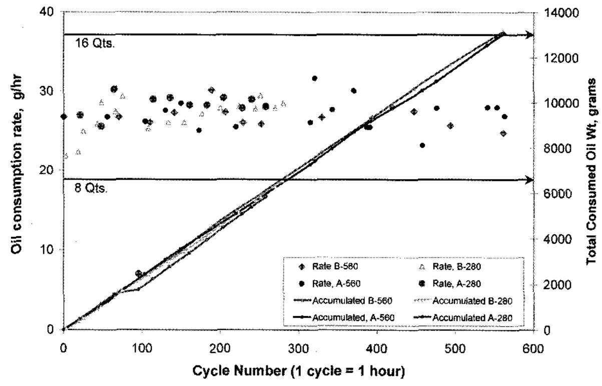

Figure 4. Measured oil consumption profiles during mild thermal aging cycle.

thermal aging cycle. Two catalysts were aged using Oil A for 280 and 560 hours respectively. Two catalysts were aged using Oil B for 280 and 560 hours respectively. Oil A and Oil B were equivalent, fully-formulated oils, except that Oil A contained 0.11 weight percent phosphorus, whereas Oil B contained only 0.06 weight percent phosphorus. Figure 4 shows the oil consumption as a function of aging time. It is important to note that the oil consumption rate was easily controlled from test to test. Repeatable, controllable oil consumption is extremely difficult to achieve using a bench engine.

After aging, cores were cut from the catalysts for activity testing. The activity testing was performed using a synthetic gas reactor (SGR) stoichiometric, perturbated, light-off test. The results are given in Table 2. STD-1 is a fresh reference catalyst core. The stoichiometric, perturbated light-off results showed that the Oil B catalyst (low P oil) reached light-off at a lower temperature for both hydrocarbon and carbon monoxide than Oil A catalyst (high P oil). These tests rank catalyst performance for CO and THC as **B>A** (for both light-off and steady-state efficiency), and for NO_x the ranking is **A.B** (for both light-off and steady-state efficiency). These results correlated well with field data generated from the use of these two oils in a vehicle fleet study.

Table 2. Synthetic gas reactor performance evaluations.

Catalyst I.D.	Stoichiometric perturbated light-Offs, T50 °C			Efficiency at 350°C, percent		
	HC	CO	NOx	HC	CO	NOx
STD-1	238	235	194	85	95	62
OilB-280	269	247	230	76	82	51
OilB-560	361	299	na	46	77	28
OilA-280	281	253	225	74	79	54
OilA-560	388	321	na	39	68	27

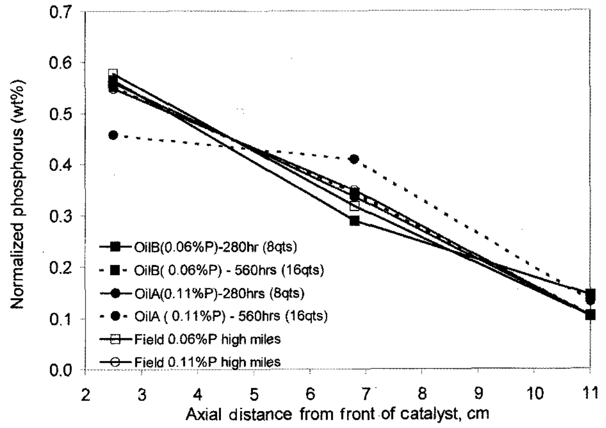

Figure 5. Normalized axial distribution of phosphorus.

Following aging and activity testing, the catalysts were cut into sections and the phosphorus deposit loadings were measured to obtain the profiles through the catalysts. These profiles were also compared to the published data from the field. After normalizing the data for sampling differences between the two studies, the results are shown in Figure 5. It is clear that the FOCAS-based oil exposure aging procedure correlates very well with the field catalysts with regard to the axial distribution of phosphorus. Hence the FOCAS system can be used to simulate real-world oil poisoning.

2.4. Further FOCAS System Developments

Subsequent to the completion of the thermal and oil poisoning studies, SwRI has been active in further developing the FOCAS system. These developments have been initiated partly to respond to customer requests, and partly to meet SwRI planned targets.

A number of different aging cycles have been programmed into the FOCAS system to recreate specific customer cycles, and new cycles have been developed to meet customer future needs. These new cycles include cycles specifically developed to utilize the FOCAS system capability of combining thermal and oil poisoning aging characteristics. Such combined aging cycles have been difficult to achieve previously using bench engines due to the difficulty of controlling the engine oil consumption.

With enhancements to the air blower and fuel injection systems, as well as modifications to the combustion zone parameters, future FOCAS systems will have the capability of aging multiple catalysts at a time with a total exhaust gas flow rate of at least 270 m^3hr^{-1} (160 SCFM).

A new heat exchanger and temperature control system are being developed to permit catalyst inlet temperatures in excess of 1000°C. While bench engine aging cycles exist with catalyst inlet temperatures as high as 940°C (Pfalzgraf *et al.*, 1996), It is understood that bench engines cannot operate much above a catalyst inlet temperature of 900°C without risking significant damage to the engine. The capability to age catalysts at inlet temperatures of 1000°C or above will be beneficial for accelerated aging of catalysts because it will result in dramatically shorter catalyst aging times.

3. CONCLUSIONS

The FOCAS system has already demonstrated the ability to recreate both bench engine thermal aging and real world oil poisoning. With the new developments currently underway, the system will be able to age multiple catalysts simultaneously, at temperatures in excess of those possible with a bench engine, and with new aging cycles that combine both the thermal and oil poisoning elements of real world catalyst deactivation. The FOCAS system will be able to match and exceed the capabilities of bench engines without the need for engine stands and dynamometers.

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REFERENCES

Drury, C. S. and Whitehouse, S. (1994). The effect of lubricant phosphorus level on exhaust emissions in a field trial of gasoline engine vehicles. *SAE Paper No.* 940745.

Ball, D., Mohammed, A. and Schmidt, W. (1997). Application of accelerated rapid aging test (RAT) schedules with poisons: the effects of oil derived poisons, thermal degradation, and catalyst volume on FTP emissions. *SAE Paper No.* 972846.

Cully, S. and McDonnell, T. (1995). The impact of passenger car motor oil phosphorus levels on engine durability, oil degradation, and exhaust emission in a field trial. *SAE Paper No.* 952344.

Cully, S., McDonnell, T., Ball, D., Kirby, C. and Hawkes, S. (1996). The impact of passenger car motor oil phosphorus levels on automotive emissions control systems. *SAE Paper No.* 961898.

Joy, G., Moliaro, F. and Homeier, E. (1985). Influence of phosphorus on three-component control catalyst: Catalyst durability and characterization studies. *SAE Paper No.* 852099.

Milliken, G. and Johnson, D. (1992). *Analysis of Messy Data Volume I: Designed Experiments.* Van Nostrand Reinhold. New York.

Pfalzgraf, B., Rieger, M. and Ottowitz, G. (1996). Close-coupled catalytic converters for compliance with LEV/ULEV and EG III legislation – Influence of support material, cell density, and mass on emissions. *SAE Paper No.* 960261.

Sims, G. and Sjohri, S. (1988). Catalyst performance study using Taguchi methods. *SAE Paper No.* 881589.

Webb, C. and Bykowski, B. (2003). Development of a methodology to separate thermal from oil aging of a catalyst using a gasoline-fueled burner system. *SAE Paper No.* 2003-01-0663.

Webb, C., Bartley, G. and Bykowski, B. (2003). Catalyst aging evaluation with exposure to 0.06 and 0.11 percent phosphorus oils using the FOCAS® burner system. JSAE 20030269, 2003.

Williamson, W., Perry, J., Goss, R., Gandhi, H. and Beason, R. (1984). Catalyst deactivation due to glaze formation from oil-derived phosphorus and zinc. *SAE Paper No.* 841406.