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ABSTRACT

Continuous improvement in vehicle emissions is necessary to meet ever tightening regulations. These regulations are advancing in both passenger and light truck vehicle markets, currently at different rates. Divergent design requirements and target markets for these platforms create unique conditions for aftertreatment needs.

To understand the performance of various products in these categories and the potential for optimization, we examine various ultrathin-wall products in the context of a close-coupled configuration in a SULEV vehicle. In addition, these comparisons are carried over to a larger platform to show the performance trends in the context of the sport utility vehicle category.

This study considers converter performance in FTP tests, examining bag data, light-off behavior, pressure drop comparisons and front and rear converter contributions. Conclusions are drawn regarding the optimization of converter substrate selection for various target design criteria

INTRODUCTION

In previous work we studied thinwall and ultra thinwall ceramic substrates [1-3]. These studies were generally a comparison of performance over the entire FTP and the application was in the context of ULEV and earlier regulation vehicles. Now we want to examine the performance of current ultra thinwall products and in the context of a newer, SULEV vehicle. This involves testing in newer SULEV test cells to account for the increased precision and accuracy required when the emission levels tested are so low.

Specifically, we seek to understand the conditions under which each of these products demonstrates its particular strengths, whether it be pressure drop, fast light-off or steady state conversion efficiency.

It has long been known that different manufacturer control strategies rely on different aftertreatment strategies depending on the goal of the platform including engine management schemes available and converter space available. Equally well known is that given these differing design strategies there is no one-size-fits-all aftertreatment strategy that would apply [4-6].

This work highlights the design areas in which different aftertreatment products have different strengths and utility.

EXPERIMENTAL PLAN

SAMPLE MATRIX

To understand the effect that results from different applications, and to acquire an understanding of new thinner-wall products, this test matrix includes three substrate systems. They represent 1) a high geometric surface area (GSA) which is a measure of surface area per unit volume, 2) a low backpressure configuration, and 3) a midrange combination. Open frontal area (OFA), a measure of cross-sectional area available for flow, ranges from moderate to high. The nominal values of the substrate attributes are shown in Table 1.

The 600/2 system in this experiment represents a strengthened substrate as described in earlier work [4]

System Name	Cell Density (cpsi)	Wall Thick (mil)	Bulk Density (g/l)	GSA (m^2/l)	OFA (%)
400/4	400	4.5	279	2.87	82.8
600/2	600	2.5	223	3.62	88.1
900/2	900	2.5	271	4.37	85.6

Table 1: Test Matrix

SAMPLE PREPARATION

Each system is made up of 4.16" (105.7 mm) diameter round ceramic substrates; 3" (76.2 mm) in length packaged two to a can for a total of .668 liters per converter.

The substrates were coated with a bimetal Pd/Rh of nominally 195g/ft³ on the front substrate and a 53g/ft³ Pt/Rh coating on the rear bed. This system is typical of those designed for a SULEV application.

The converter systems were canned at an in-house prototype facility using standard packaging methods in a “take-apart” can which is designed to ease reconfiguration and testing but minimize thermal mass in order to approximate typical automotive converter systems.

AGING

Aging was performed using CARB rapid aging Test-A procedure. This is a four-mode procedure; the details are shown in table 2. It uses 825°C inlet and an air injection phase. Aging was performed on a 5.4L V8 engine, four converters at a time. The systems were aged for 100 hours to approximate a 120,000mi life.

Mode No.	Duration (sec)	Description
1	40	Stoichiometric Fuel-Air Ratio (Closed Loop)
2	6	Fuel-Rich Operation (Power Enrichment) (Open Loop)
3	10	Fuel-Rich Operation with Air Injection (Open Loop)
4	4	Stoichiometric Operation with Air Injection (Closed Loop)

Table 2: Aging cycle

Converter substrate temperatures, as well as inlet and outlet exhaust gas temperature were monitored throughout the aging process. Exhaust pressures for each converter were also recorded along with selected engine parameters, including coolant temperature, mass air flow and air fuel ratio.

VEHICLE

The vehicle used for testing has a 2004 calibration 2.0L I4 SULEV engine using gasoline fuel. This engine is mated with an electronically controlled four-speed automatic transmission. The vehicle uses Dual Overhead Camshafts (DOHC) to control four valves per cylinder with continuous variable valve timing (CVVT) on the intake cam. CVVT offers improved performance at high engine speeds and increased torque at low speeds, as well as improved fuel economy. The vehicle uses electronically controlled multipoint fuel injection (MFI) with a coildirect ignition system.

The original exhaust system consists of a single close-coupled three-way catalyst (with a volume of 0.88L) integrated into the exhaust manifold and located directly in front of the engine followed by an underbody catalyst, a center muffler, and a main muffler at the tail pipe.

Two identical vehicles were purchased to facilitate testing. Correlations were done between them to validate the use of the two vehicles and these show good repeatability. The vehicles were broken in for 4000 miles before testing.

TEST PROCEDURE

The facility used for the test is equipped with the latest SULEV-capable measurement equipment and ambient controls. A 48” single roll chassis dynamometer was used for the FTP tests. Emissions measurements were taken continuously before and after the close-coupled converters and also bag data was measured at the tailpipe.

For catalytic converter testing the procedure consisted of one (1) prep cycle followed by three (3) EPA75 C/H emission test cycles. The prep cycle used was the “EPA Urban Dynamometer Driving Schedule”, which is also known as the LA4 Prep Cycle. The emission test cycle used was the “EPA Federal Test Procedure”, also known as EPA FTP75 C/H. Following the prep cycle and between each emission test the vehicle was left to soak for a minimum of 12 hours.

All chassis roll emission testing was completed per the EPA guidelines for the FTP75 and the LA4 tests. The test facility used meets all the requirements for EPA Certification Testing and has the necessary equipment to test SULEV vehicles. The system utilized for testing was the Horiba MEXA-7200SLE for Super Ultra Low Emissions Analysis. This system features ultrasensitive SLE (super low emission) analyzers, a heated sample handling system, and bag minidiluter.

RESULTS

CONTINUOUS DATA

Looking at the full-test emissions as a unit, the overall advantage of the high-GSA 900/2 product is readily apparent in all emissions species. Figure 1 shows the accumulated hydrocarbon emissions. The 900 cell substrates show a marked advantage during the steady state and hot start phases of the tests.

The divergence of the curves illustrates where the overall conversion efficiency is providing conversion at all stages of the test. Looking also at the early part of the test, it is clear that the 900/2 reaches its highest efficiency early and continues to perform throughout. By contrast, the 600/2 has similar performance in the early part of the test, until the hard acceleration at the beginning of the second hill show some breakthrough versus the higher GSA system.

The 900/2 superior performance comes in part from the steady state region, which is also illustrated by way of conversion efficiency later in the report, and in the hot-start at the beginning of bag 3 where the high GSA of the 900/2 again results in an advantage early in the bag. Overall, the 600/2 shows a 20% improvement in performance over the 400/4 and the 900/2 shows a nearly 40% improvement over the 400/4. A close look at the very early stages of light-off will be shown in more detail in the next section.

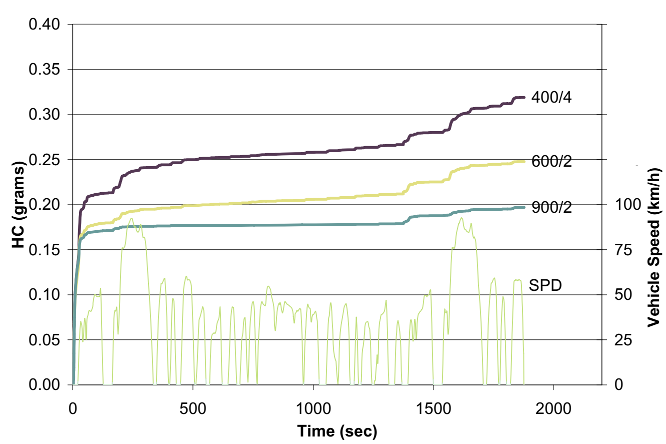

Figure 1: Full FTP accumulated hydrocarbons

The oxides of nitrogen (NOx) show a more complex picture in Figure 2. By the end of the full FTP, the performance ranks of the three systems align with the ranks of their GSA. However the ranks have crossover points earlier in the test and show that the largest performance contributions of the higher GSA 900 cell product lie in the steady state operation of bag two and in the hot start region of bag three. Overall, the results show the 600/2 and the 900/2 achieving a 10% and nearly 20% improvement, respectively. More detail is discussed in the Light Off section.

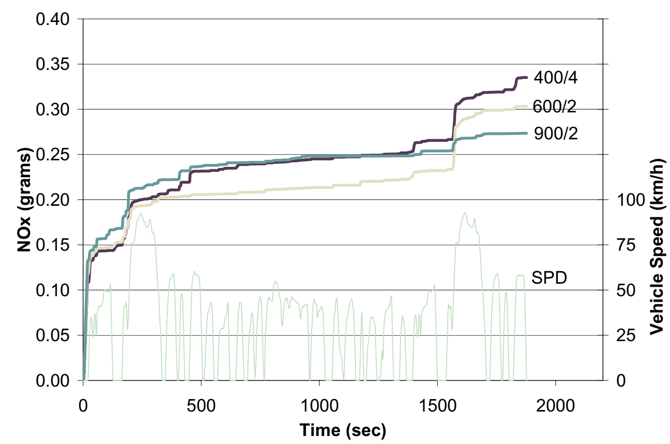

Figure 2: Full FTP Accumulated NOx

In Figure 3 the carbon monoxide (CO) shows a striking advantage for the 900/2. As is typical in current converter designs, the CO emissions are well below the regulation levels, the gains in this species are not a matter for design criteria, but do support the trends seen in other emissions.

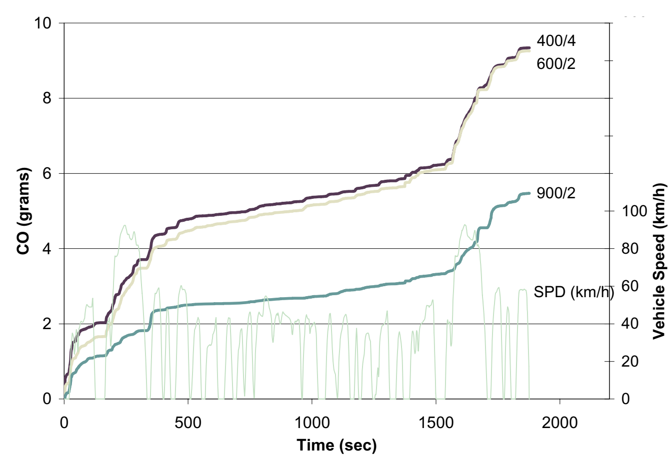

Figure 3: Full FTP Accumulated CO

LIGHT-OFF

By turning the focus to the light-off region of the test, the first 40 seconds, we can discern the relative advantage of the various cell densities in an area that is of great concern to design teams. While some control strategies rely on aftertreatment in the steady state regions, other strategies look for aftertreatment gains in a very narrow band of operation in the transient part of the cycle. By focusing in this area we show that the performance rank changes for a short time in this critical region.

In Figure 4 the extremely low bulk density of the 600/2 substrate contributes to a faster light-off than the heavier counterparts. The 900/2 benefits from the higher GSA for reactions and shows early conversion, but the faster heat up of the 600/2 shows itself to be acting within that critical first 25 seconds, specifically between 7 and 23 seconds where the emissions are the lowest for that system. Although the advantage is small, it highlights an area that can be exploited in certain design strategies.

Both the 900/2 and 600/2 continue to show their light-off advantage versus the 400/4 product through to 40 seconds shown in Figure 4, and indeed through to the hard acceleration of the second hill at 160 seconds.

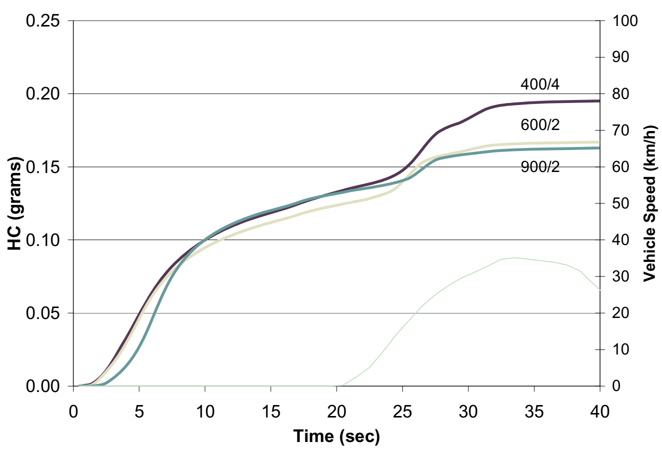

Figure 4: Light-off Accumulated HC

While we see in the figure above that the 600/2 performs in the same range as the 900/2 in the early part of the transient phase, we know that the difference in GSA indicates the effect of the bulk density on its performance.

To understand the magnitude of the potential for this effect, Figure 5 shows the temperature response of the three systems at 3.8cm (1.5") on the centerline. The lighter weight 600/2 is clearly responding to the temperature changes in line with its lighter weight, heating up to reaction temperature faster.

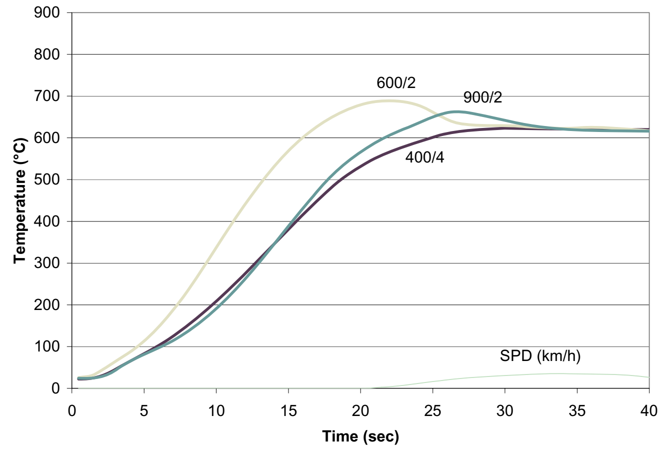

Figure 5: Temperature response at 3.8cm (1.5") at the centerline

In the early part of the transient phase, the heavier, higher GSA 900/2 lags in performance behind the lower cell density samples. By 200 seconds, in the second "hill", the performance of the 400 cell begins to fall away from the 600 cell sample. This rank continues through bag one shown in Figure 6. During the last part of bag 1, the strong performance of the 900 cell product brings it down toward crossover with the 400 cell product, overcoming its light-off lag. The 600/2 system continues to perform well throughout bag 1.

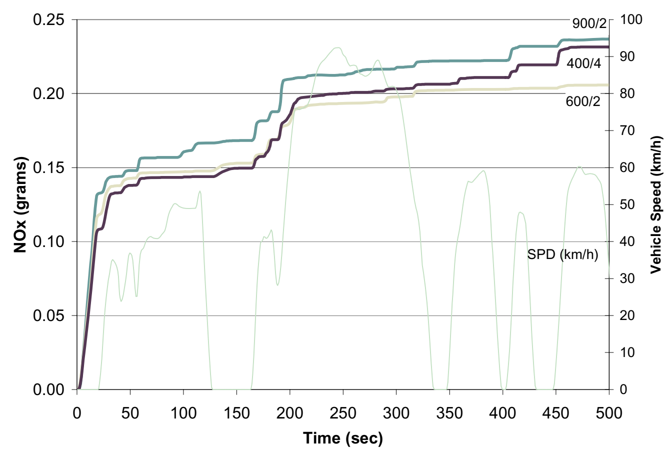

Figure 6: Bag 1 Accumulated NOx

Overall, the relative performance of the three systems studied shows different benefits in different phases of the FTP. The 600/2 system performs best in converting hydrocarbons in the early light-off region of 7-23 seconds on this vehicle, and in bag 1 in NOx conversion, while the 900/2 outperforms both other systems for the remainder of the test in both HC and NOx

CONVERSION EFFICIENCY

The conversion efficiency throughout the FTP shown in Figure 7 and the close-up of the second hill in figure 8 show the steady state performance of the 900/2, this time highlighted in the higher flow rate regions of the FTP. During the strong accelerations a noticeable breakthrough is evident for the 600 cell and 400 cell systems, while the 900 cell maintains its high conversion efficiency. This is clearly one mechanism by which the 900 cell diverges, as noted in the discussion of accumulated emissions, during the hot portion of the test.

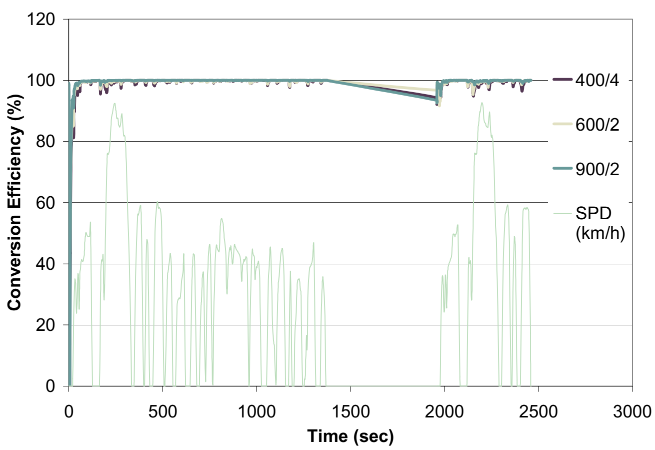

Figure 7: Hydrocarbon Conversion Efficiency

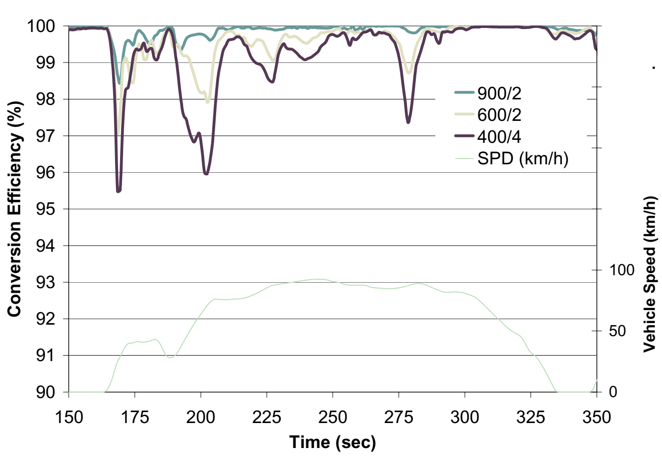

Figure 8: Hydrocarbon Conversion Efficiency at Hill 2 in Bag 1

A focus on the conversion efficiency during the light-off portion of the test shows the different story of the 600/2 advantage during heat up. The conversion efficiency in the first 15 seconds is shown in Figure 9. Because of this faster thermal response, the time to reach 50% conversion efficiency is approximately one half second faster for the 600/2 system. While the crossover with 900/2 occurs at approximately 8 seconds, we recall from the accumulated emissions that the effect of this pace lasts through 23 seconds in overall emissions results.

As a baseline, the 400/4 lags behind the 600/2 by 2 seconds and this is manifested in higher accumulated hydrocarbons throughout the test.

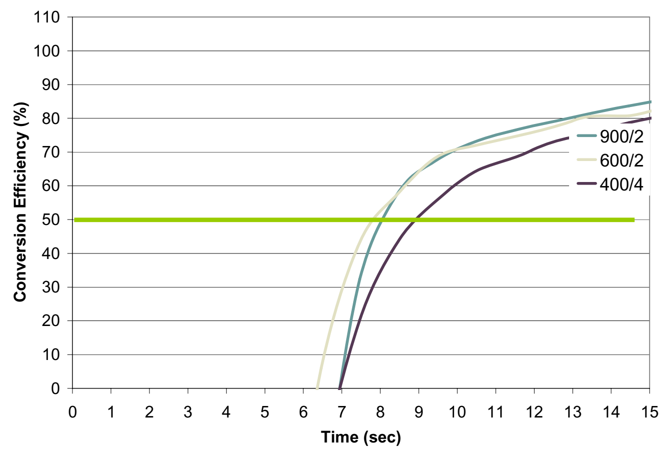

Figure 9: HC Conversion Efficiency in first 15 seconds

COMPARISON TO UNDERBODY CONTRIBUTION

The final area of interest is the contribution of the underbody system. By comparing the tailpipe bag data to the continuous data after the close-coupled converter, we can judge the relative contribution by the underbody converter and determine the points of the cycle during which it is needed.

In Figures 10 through 15, the continuous line represents the accumulated emissions from the close-coupled converter system, the dashed mark at the end of the cycle represents the tailpipe bag emissions and the thicker grey mark at the end of the cycle represents the SULEV regulation for emissions.

It is important to recall that the converter systems tested in this study represent 0.22L less volume than the original equipment converter system. Therefore when analyzing the compliance with the SULEV regulation, this context must be considered.

Figure 10 shows that the 400/4 product does not meet SULEV by a significant margin. Moreover we can see fractional but significant breakthrough from the close-coupled (CC) converter that is being picked up by the underbody in hydrocarbon conversion. This data highlights the absolute need for higher GSA to meet a SULEV regulation.

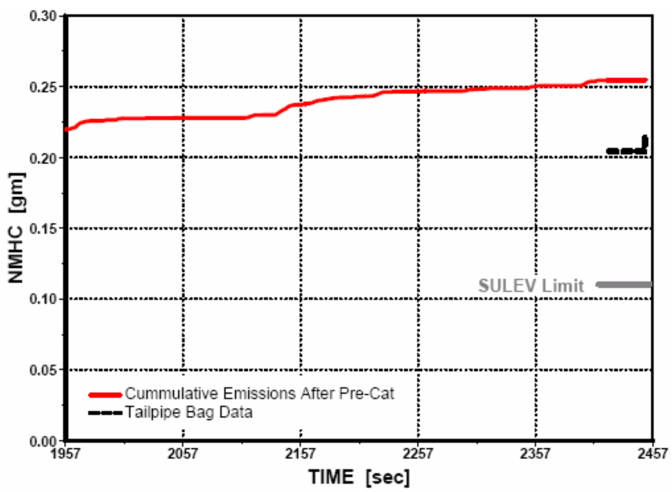

Figure 10: Phase 3 Hydrocarbon Emissions for 400/4 - accumulated, bag and regulation

Figure 11 shows the same graph but for NOx emissions. For this species, as in the hydrocarbon analysis, the 400 cell close-coupled system does meet the regulation, relying on the underbody converter to do the bulk of the "work".

With the gap between close-coupled NOx emissions and tailpipe bag NOx emissions even larger than for hydrocarbons, this highlights the need for underbody volume to meet the NOx regulations, while showing that NOx will be the main target of that underbody component of the converter system.

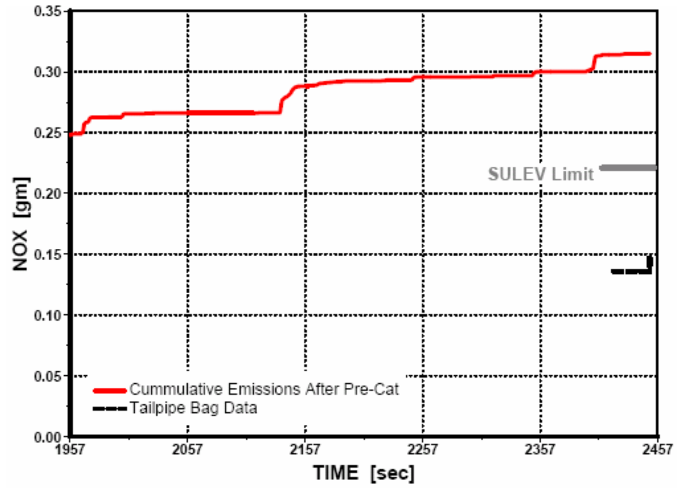

Figure 11: Phase 3 NOx Emissions for 400/4 - accumulated, bag and regulation

The 600/2 product is closer than the 400-cell system to meeting SULEV HC regulations as shown in Figure 12, and the close-coupled converter is capable of doing almost all of the converting as evidenced by the solid and dashed lines being nearly on top of each other.

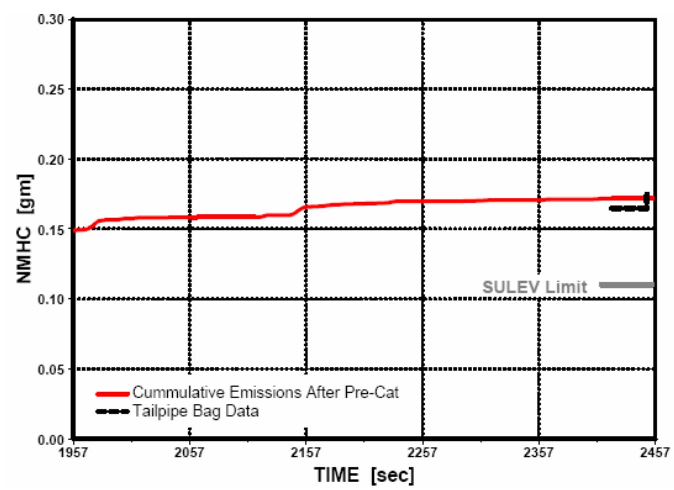

Figure 12: Phase 3 HC Emissions for 600/2 - accumulated, bag and regulation

In Figure 13 we see that the 600/2 system does meet NOx standards, again relying on the contribution of the under-body (UB) converter. Design options are evident in optimization of volume and/or precious metal (PGM) loadings to meet SULEV regulations without the under-body converter. When using an under-body converter to close this gap, however, this shows that with NOx as the main target an emphasis on low back-pressure can be exploited.

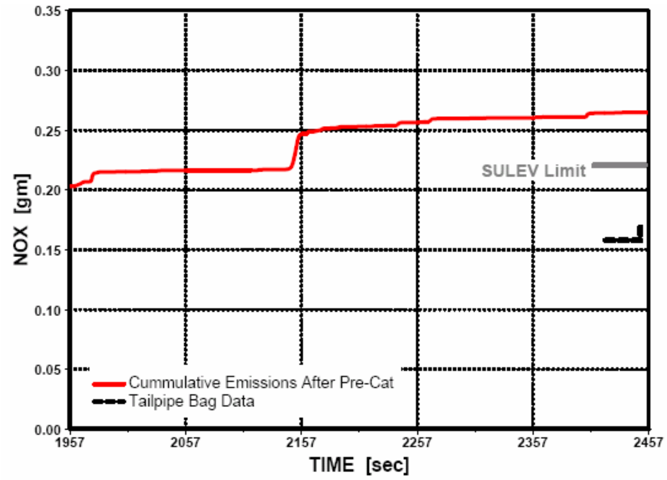

Figure 13: Phase 3 NOx Emissions for 600/2 - accumulated, bag and regulation

The 900/2 product comes the closest of all the systems tested to meeting the SULEV regulation, with a 6% improvement over the 600/2 final bag numbers. Recalling that we are testing a smaller volume than the original equipment in order to highlight design potential, we can estimate that slightly larger volumes will close this gap for all systems tested, while maintaining the same rank and relative differences between systems tested. From the results shown in figure 14 below, we again see that this can be accomplished with the volumes in the close-coupled position. This is expected from the higher conversion efficiencies seen already for this system.

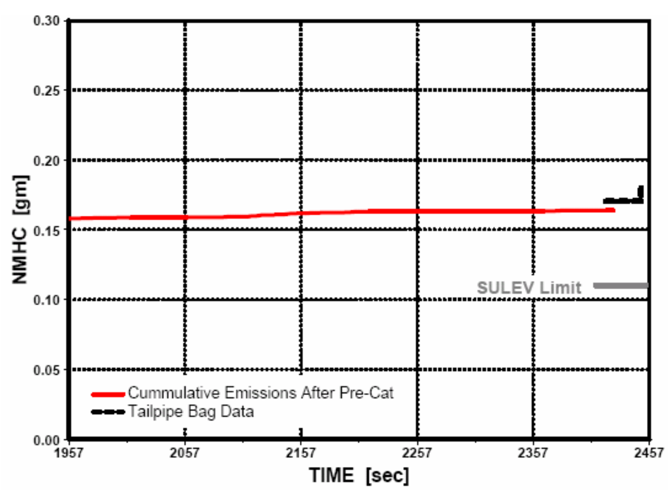

Figure 14: Phase 3 HC Emissions for 900/2 - accumulated, bag and regulation

In Figure 15, the NOx emissions view shows that the system meets NOx limits through the contributions of the UB converter. While the conversion of NOx from the CC component is significantly better than the lower cell density systems, the UB component plays a necessary role in meeting the NOx targets.

Again this highlights the role of the underbody converter in NOx conversion and opens the door to exploiting low back-pressure solutions to meet the regulations in cases where engine out HC levels are met by the close-coupled portion of the system. At the same time, the improved NOx conversion efficiency (greater than 10%) from the close-coupled component in the 900/2 system compared to the 600/2 system allows more design room for specific strategies that may be useful for future legislation or application-specific design requirements.

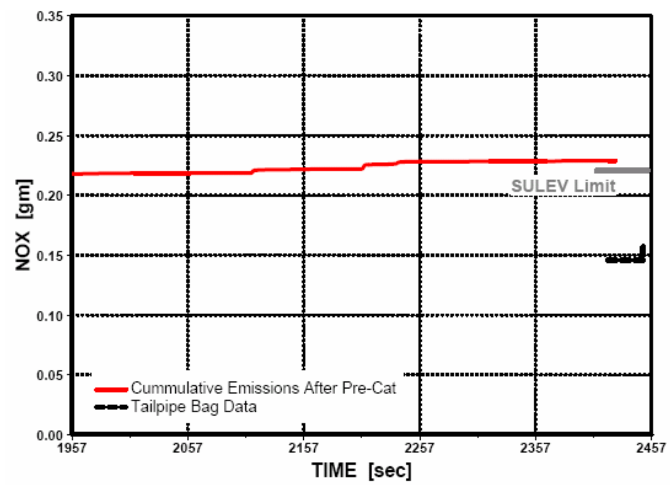

Figure 15: Phase 3 NOx Emissions for 900/2 - accumulated, bag and regulation

PRESSURE DROP

Pressure drop values calculated from the actual dimensions of the substrates used in this study are shown in Figure 16. These illustrate the balance made with improved conversion efficiency. While the 900 cell system has the highest pressure drop along with its improved overall conversion efficiency, the 600 cell system is significantly lower and indeed is close to the pressure drop in the 400 cell system.

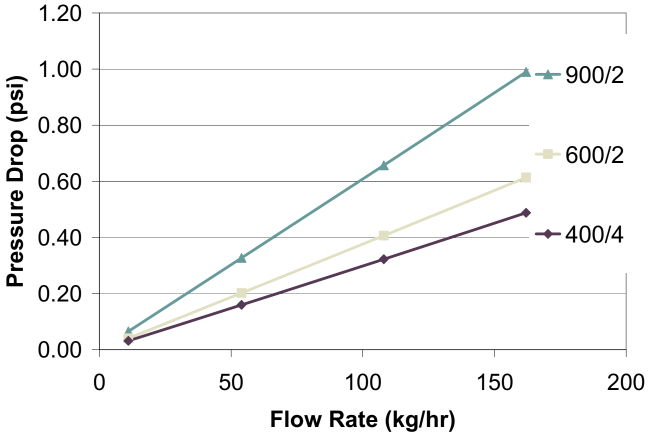

Figure 16: Calculated Pressure Drop

When comparing the strategies available based on the pressure drop comparisons, we must keep in mind a systems approach that can exploit the conversion efficiency differences between the products and translate this performance difference into differences in volume requirements.

As we saw in the earlier sections of this work, more substrate volume is required for a lower cell density solution to meet conversion targets. This will clearly affect the overall pressure drop when designing a system and specific calculations must be made.

CONCLUSION

This work compares the relative performance of three ceramic substrate converter systems; 900/2, 600/2 and 400/4 in the context of light-off, steady state, and hot start areas of the FTP. It makes comparisons with respect to close-coupled position and underbody position in a converter system. It further compares the systems in the context of pressure drop. Each area of performance comes with tradeoffs that designers can exploit to maximize the performance for a given application.

Overall, the 900/2 ceramic substrate performs best over the complete FTP cycle with respect to both HC and NOx emissions. It provides a 20% and 8% advantage over 600/2 on HC and NOx respectively, from continuous emissions measurements, and a 39% and 19% advantage over 400/4 in the same constituents.

When looking at only light-off, the 900 and 600 perform similarly in the first 30 seconds, with the 600/2 having a small area of superior performance in the very early light-off regime from 7 to 23 seconds. In addition, the 600/2 provides a lower pressure drop than the 900/2 when volume is kept constant.

When taken in the context of the underbody location, the 400/4 performs well in converting "breakthrough" emissions, particularly NOx emissions, although the improvements available from the higher GSA products are still valid in the UB location.

Converter systems can be designed to optimize emissions and performance given a variety of different operating conditions and control strategies. Taking advantage of individual attributes and the areas of the FTP in which they contribute most provides direction for this optimization.

ACKNOWLEDGMENTS

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