2007-01-1262

Development of Advanced Metallic Substrate Design for Close Coupled Converter Application

Klaus Müller-Haas, Mike Rice
Emitec Inc

Ronald Dean, Randal Olsen, Joseph Adams
DaimlerChrysler

Lisa Manasse, Michael Chruch
Johnson Matthey

ABSTRACT

The implementations of the Tier 2 and LEVII emission levels require fast catalyst light-off and fast closed loop control through high-speed engine management. The paper describes the development of innovative catalyst designs. During the development thermal and mechanical boundary conditions were collected and component tests conducted on test rigs to identify the emission and durability performance. The products were evaluated on a Super Imposed Test Setup (SIT) where thermal and mechanical loads are applied to the test piece simultanously and results are compared to accelerated vehicle power train endurance runs. The newly developed light-off catalyst with Perforated Foil Technology (PE) showed superior emission light-off characteristic and robustness.

INTRODUCTION

More stringent emission standards for gasoline applications in the United States and Europe require the development of high efficient durable catalyst systems. Close coupled converter systems benefit from higher exhaust gas temperature during engine cold start and extremely fast catalyst light-off is achieved to convert hydrocarbons, carbon monoxide and nitrogen oxides in harmless gases. However, limited space in the engine compartment requires very durable small high performance catalyst systems to achieve also engine power goals. For example, cascaded converter systems provide the feature of fast light-off through higher power density with the compromise to tune overall back pressure performance.

Installing the catalyst closer to the engine results in higher operating temperatures for the catalyst. Therefore higher thermal and mechanical loads are expected compared to toe board or underfloor converter systems. Also thermal loads through cylinder exhaust gas pulsations are higher and less space for flow development lead to more challenging cylinder gas maldistribution over the catalyst. As a result, thermodynamic stressors are higher for close coupled converter systems. Vibration loads induced by the engine are of more interest while the vibration loads caused by poor road surfaces are usually in a low frequency range and are negligible.

This paper describes the development of a high performance light-off catalyst for close coupled position. It is shown how to quantify main stressors applied to a catalyst system and how component rig testing was used for product comparison during development phase. Furthermore rapid endurance vehicle tests were conducted to prove robustness in real world environment.

A converter systems with PE-Metalit® was developed with extremely good light-off performance and superior robustness.

STRESSORS FOR CATALYST SYSTEMS

The critical stressors for catalytic converter systems can be described as follows [1,2,3]:

- temperature and temperature change rates cause thermal expansion and contraction resulting in thermal stresses within the matrix

- flow uniformity and maldistribution of exhaust gas cause thermal gradients

- vibration loads and resonance frequency design capability

- exposed transient temperature conditions through exothermal reaction during transient vehicle operation, e.g transition from high load conditions to closed throttle operation with fuel cut off

Stressors can be identified by data collection, compared to existing database and applied on component test setup for design comparison.

DATA ACQUISITION

The range of loads for converter systems in exhaust systems is extremely complex and is typically an accumulation of oscillating mechanical loads, temperature, and exhaust flow loads with superimposed corrosive influences. The mechanical load factor is usually a function of exhaust system configuration and the catalyst location and engine power and engine speed level. Decoupling components can be installed in the exhaust system upstream of the catalyst to reduce the vibration load induced by the engine. The thermal load factor is caused by rapid catalyst heat-up during vehicle acceleration followed by cooling down intervals. This applies thermal shock loads to the catalyst. Both load factors are stressors and can be acquired and quantified. Figure 1 shows the exhaust system with close coupled converters compared to a system with toe board converters.

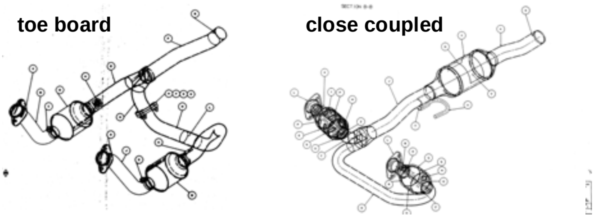

Figure 1: Typical system architecture for close coupled and toe board converter systems

Close coupled systems benefit from faster heat up during engine start but experience also more dynamic thermal conditions. The temperature was recorded for close coupled and toe-board converter position using a production medium duty truck equipped with a V8 engine. Catalyst bed temperature was measured for both configurations using a 1200cpsi Metalit® instrumented with fast responsive 0.5mm K-type thermocouples. The recorded temperature profiles during the US06 test cycle are compared in Figure 2. Catalyst bed temperature for the close coupled catalyst is up to 80°C higher compared to the toe board position.

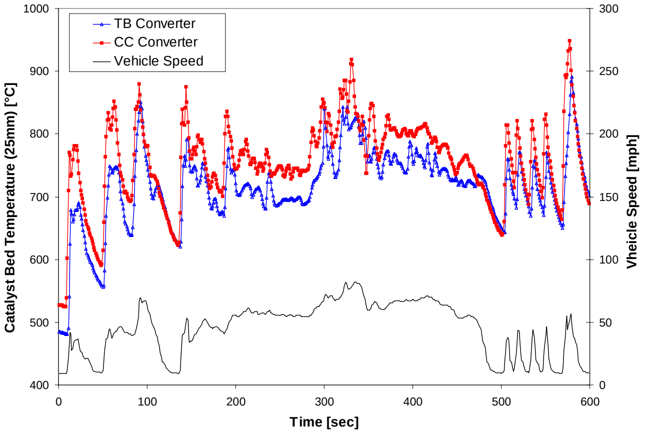

Figure 2: Recorded bed temperature as a function of catalyst location

The temperature data are used to calculate temperature change rates to quantify thermo-mechanical loads applied to the catalyst. Figure 3 shows the data for the close coupled converter system. Maximum positive temperature transients above +6,000 K/min are calculated during sharp vehicle acceleration. Negative temperature change rates of –1,500 K/min are calculated during vehicle deceleration.

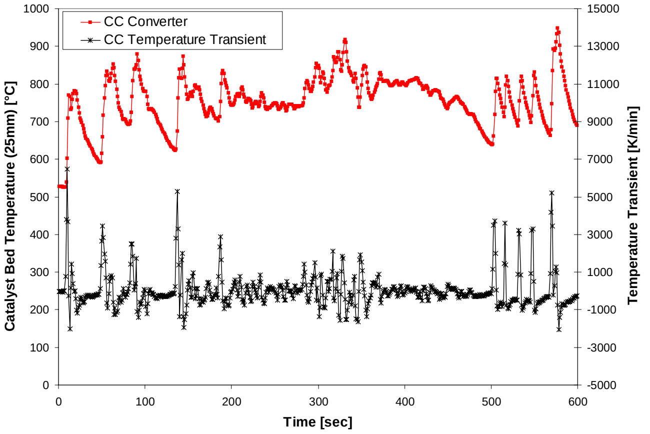

Figure 4: Temperature and calculated temperature transient for close coupled catalyst position

For comparison of the thermal loads absolute temperature and calculated temperature transient for each data point is plotted in a XY-chart as shown in Figure 5. One counter-clockwise loop represents a heat-up cycle followed by cool down interval during deceleration. The developed "Spider-Chart" gives a good comparison for the thermal condition comparing the close coupled system versus the toe board system using the same catalyst.

This evaluation method was used during the design phase to quantify the thermo mechanical loads.

Frequency- analysis and Rainflow -analysis are used to quantify cycling loads.

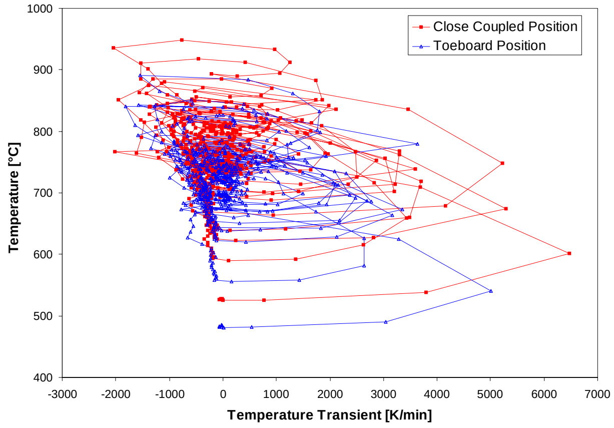

Figure 5: Temperature Spider Chart for close coupled and toe board catalyst position

During the development vibration loads were also investigated. The converter system was instrumented with accelerometers to record mechanical loads at WOT engine operation. Figure 6 shows recorded vibration values of the converter axis as a function of engine speed. The z-axis represents the longitudinal axis of the converter system and x- axis and y-axis shows the radial vibration loads. The signals are transferred from the time domain into the frequency domain and power spectral density numbers are calculated for comparison.

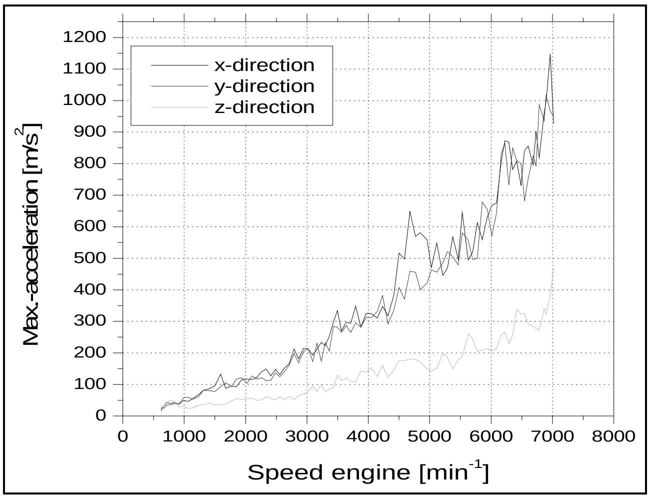

Figure 6: Example of the vibration loads and evaluation

Both load conditions, thermal and mechanical, are later used to develop generic boundary conditions to simulate thermo-mechanical stressors in accelerated component test procedures.

SUBSTRATE DESIGN DEVELOPMENT

Different substrate designs were selected to compare emission performance and product robustness in component tests and vehicle endurance tests. The following chapter describes the architecture of different designs engineered in the development phase.

DUAL-MANTLE (DM) DESIGN

Figure 7 shows the architecture of the Dual-Mantel Design. The system consists of the matrix, the inner mantel and outer mantle. A small air-gap is formed by downsizing the outer mantle on each side to thermally decouple both mantles. The outer mantle is engineered to handle mechanical stress. The inner mantle thickness is minimized to lower thermal inertia. Modeling work was done to quantify thermal characteristic as a function of the inner mantle thickness during transient operation. Ideally, the mantle temperature follows quickly the matrix temperature to minimize differential expansion and contraction during thermo-cycling.

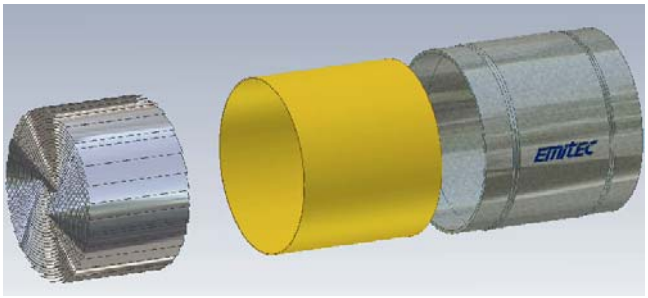

Figure 7: Dual Mantle Architecture (DM-Design)

Exhaust gas temperatures and mass flow were recorded for vehicle WOT acceleration and deceleration. The exhaust gas temperature and calculated temperature of the inner mantel are compared in Figure 8. The 0.5mm mantel design shows a faster thermal response than the 2.0mm mantel design. Though, the temperature cycling range is higher for the thinner mantel design it is expected to improve durability through the reduced temperature difference between the substrate matrix and the mantel and therefore lower stress between the foil-mantel joints.

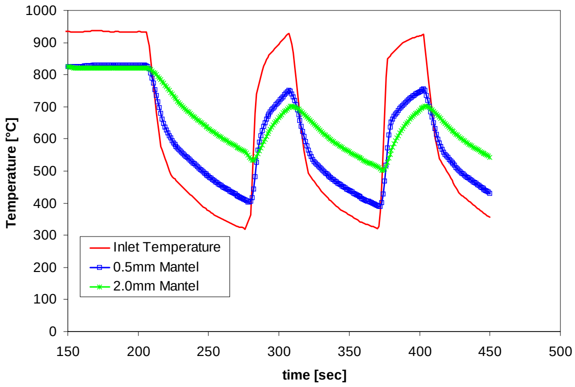

Figure 8: Calculated mantel temperature as a function of mantel thickness

HIGH DURABLE (HD) - DESIGN

The HD design is constructed with an inner corrugated foil layer which is wrapped around the circumference of the wounded matrix. The principle construction is illustrated in Figure 9. The matrix is completely brazed to the HD mantel. The connection between the HD mantel and outer tube is seen by a small brazing stripe. The HD-Design has surperior robustness through the minimized thermal mass of the HD mantel and the increased flexibility. (compare reference [3]).

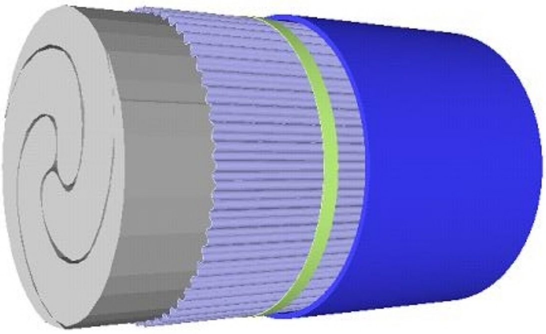

Figure 9: High-Durable architecture (HD-Design)

This innovative HD design incorporates the following advantages:

- thermal mass reduced by more than 300% compared to a 0.5mm inner mantel. The HD-mantel is less stiff because of the corrugated shape.
- the corrugated HD-mantel is thermally decoupled from the outer mantel
- the HD-mantel allows higher degree of freedom of the matrix in axial and radial direction for expansion, contraction, and rotation

The DM and HD architecture can be applied to all matrix structures for example different cell densities, foil structures like Transferal Structure (TS), Longitudinal Structure (LS) and Perforated Foil Matrix (PE) [4].

ROBUSTNESS TESTING

Accelerated lifetime testing strategy was used to study the performance of different substrate designs under defined boundary conditions. The accelerated testing philosophy is very helpful to determine product life for one specific failure mode under extreme mechanical and thermal loads during the development phase [1]. The test is very useful for design discrimination, e.g. comparison of design A with design B, and even more useful when confirmed with vehicle endurance results. However, rig testing has limits such as simulating exhaust gas maldistribution, pulsations effects due to periodic events like missfire and fuel cut-off etc [5,6].

The substrate diameter and length was kept constant for all samples. Substrate cell densities, foil thickness, and mantel configuration were changed. Samples were prepared with inlet and outlet cones and extension pipes for installation in a 45° test rig. Additionally, thermocouples and accelerometers were installed to monitor thermal and mechanical loads during the test. Figure 10 shows the test fixture and setup used for the development.

Following test conditions were selected for the superimposed (SIT) test procedure:

- heat source: exhaust gas burner with complete combustion
- minimum temperature 330°C
- maximum temperature 930°C
- heat-up rate: 6,000 K/min
- cool down rate: 2,500 K/min
- exhaust gas mass flow during heat up 350 kg/hr
- exhaust flow during cool down 150kg/hr
- vibration load profile with continuous 13grms level with defined PSD characteristics
- burner control with 0.75mm K-Type thermocouple installed 2mm after front face to record substrate bed temperature
- flow profile with >0.9 uniformity index

The applied temperature and temperature transients are plotted in a time history chart in Figure 11. The system is stabilized for 2 minutes and cycled eight times between the specified upper and lower temperature. The converter system is tested to mechanical failure which is automatically sensed by the test equipment.

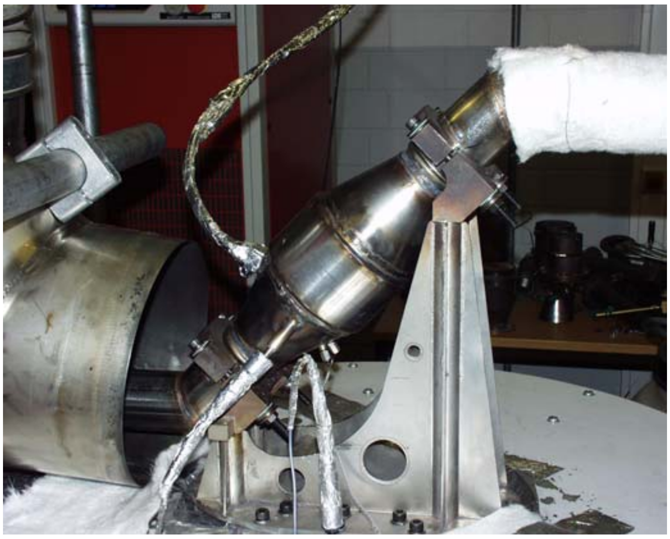

Figure 10: Test setup with controlled burner system and 45° test rig with installed converter (SIT Test)

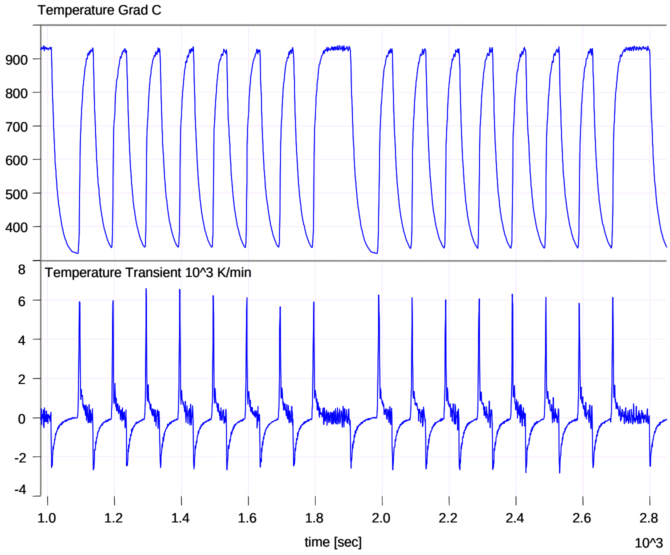

Figure 11: test Setup with controlled burner system and 45° test rig with installed substrate.

COMPONENT TEST RESULTS AND DISCUSSION

Standard substrates with straight through channels were tested as well as substrates with perforated (PE) foil.

The PE substrate design is shown in Figure 12. The corrugated and flat foil layer is perforated. Mixing chambers in the matrix are visible after matrix winding. Depending on flow maldistribution pressure gradients are build up within the structure. Radial flow within the PE structure is possible and flow uniformity improved towards the outlet of the catalyst. The thermal mass of the substrate is dramatically reduced. Minimizing the heat capacity is advantageous for heat-up during vehicle cold start and faster light-off is expected. The second brick heats up faster in a dual brick or cascaded converter arrangement.

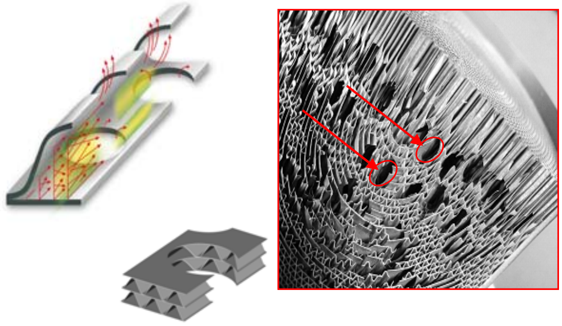

Figure 12: PE Metalit®

Table 1 lists the physical properties of selected substrate matrixes for the DOE.

Design (cpsi-foil thickness)	Foil Structure	Heat Capacity [J/K/ltr]	Back Pressure [%]	Emission Ranking for Light-Off Performance
800cpsi-40µm	Std	379	100	O
800cpsi-25µm	Std	260	91	+ +
600cpsi-40µm	Std	330	77	-
600cpsi-50µm	PE	250	80	+ +

Table 1: physical properties of tested substrate matrixes (+) indicates better than, (-) indicates worse

As shown in Table 1, thin foil technology reduces thermal mass. Thermal mass of a 600-50µm PE substrate is comparable to the 800-25µm design. System back pressure is calculated for WOT condition and is higher with thicker foil and higher cell density as expected. Computational tools were used to estimate the light-off characteristic of the standard designs as a function of cell density and foil thickness. The high cell density 800cpsi product with 25µm foil outperforms the 600cpsi and 800cpsi Metalit with 40µm foil as shown in Figure 13. Prediction of the light-off performance of the 600-50µm PE Metalit was not possible with current catalyst models. However, general test results showed superior heat-up benefits of PE technology compared to standard substrates designs and better light-off characteristic. Better light-off performance of the 600-50µm PE-Metalit® is expected compared to 600-40µm standard design due to lower thermal inertia. Back pressure is calculated for each design assuming a uniform inlet flow condition. The 600cpsi products show lower flow restriction compared to the 800cpsi substrates.

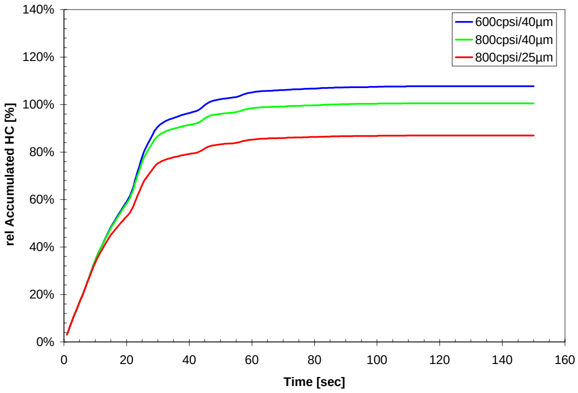

Figure 13: Predicted HC Tailpipe emissions as a function of substrate design

All samples were tested using the Super Imposed Test (SIT) procedure to determine life-time under defined boundary conditions. The amount of test cycles until EoL (End-of-Life) are listed in Table 2 and can be summarized as follows:

- an improvement factor of 4 - 5 can be seen by comparing the 800-25µm HD design with the 800 DM design
- the HD design shows superior life time
- the 600-50µm PE DM design show 2 to 3 time longer life time compared than the 600-40µm DM Metalit®
- Substrate life of the 600-50PE DM design is similar to 800-25µm HD

Design (cpsi, foil thickness)	Foil Structure	Architecture	Total Cycles [%]
800cpsi-25µm	Std	DM	100
800cpsi-25µm	Std	HD	430
600cpsi-40µm	Std	DM	140
600cpsi-50µm	PE	DM	350

Table 2: EoL cycles of tested substrate designs

VEHICLE EMISSION TESTING

Figure 14 shows the accumulated HC tailpipe emissions during FTP cold start using a production vehicle with a V6 engine. Catalyst were dyno aged to simulate 50k road aged conditions and were installed in close coupled position.

The system with the 600-50µm PE Metalit® shows faster light-off compared to the 600-40µm standard design using the same PGM level (washcoat technology and precious metal loading are proprietary information).

A faster heat-up and heat-through is achieved with the 600-50µm PE catalyst and overall, HC tailpipe emissions are 40% lower compared to the 600cpsi catalyst without perforated foil.

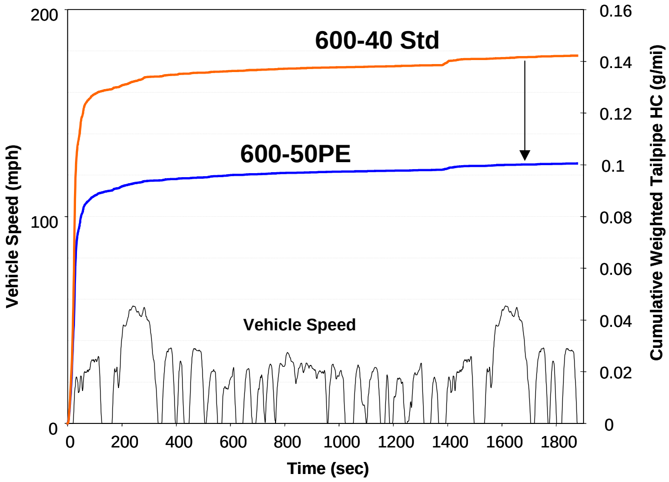

Figure 14: Light-Off performance during FTP cold start

VEHICLE VALIDATION TESTING

Selected catalyst systems were tested on a production vehicle in a rapid endurance test cycle. The Spider-Chart (Fig.15) shows the thermal conditions during the endurance test. The endurance driving schedule consists of extremely rapid WOT acceleration and deceleration intervals followed by cruises to stabilize the thermal condition. Maximum heat-up rates of 12,000 K/min and cool-down rates of –4,000 K/min are applied to the catalyst. Catalysts were regularly inspected to confirm robustness.

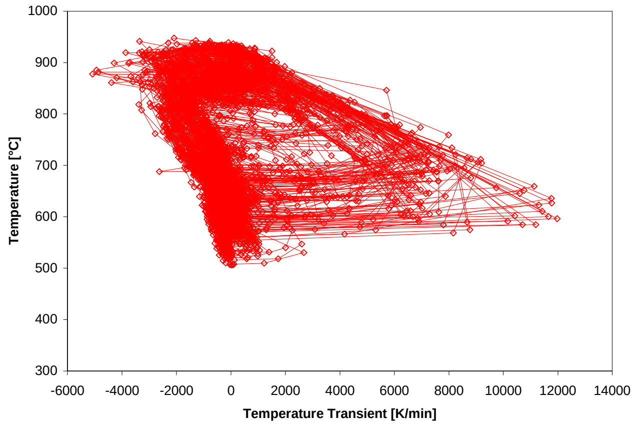

Figure 15: Spider-Chart Vehicle Endurance Test Cycle

Figure 16 compares the product life times achieved in component test and accelerated vehicle endurance tests. The life time of the DM Metalit with 600-50µm PE foil was highest. The improvement of the life by upgrading from DM to HD design is also visible comparing the 600-40µm systems.
It is very important to notice that product life achieved during accelerated SIT component testing does show different life time in the vehicle testing. The 600cpsi-40µm HD design shows longer life in the SIT and vehicle test compared to the 600cpsi-40µm DM design. The 600-50µm PE product demonstrated in the vehicle significantly more robustness compared to the 800cpsi system while SIT test cycles applied were comparable. Even at more severe thermal loads within vehicle testing product failure mode is simulated in the accelerated SIT test in approximately 10% of the time.

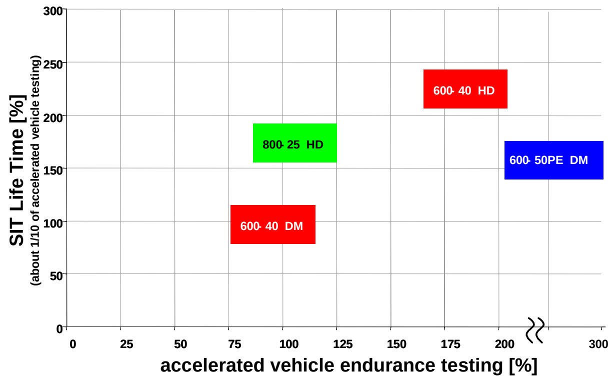

Figure 16: Vehicle Endurance test results versus component test results

The importance of well-developed rig test procedures, which correlate to real world events, can be noted in these facts:

- While every product can be tested in an accelerated fashion, the risk especially in the beginning is that phantom failure modes are produced leading to “over” engineering of the product.
- While both vehicle and rig tests are “accelerated”, the SIT test produced the same failure mode using about 10% of the time required to do that same in the accelerated vehicle tests. While this reduction in “time required” saves cost, the real savings is that the product development cycle is dramatically shortened, improving productivity for both supplier and car manufacturer.

CONCLUSION

Following conclusions can be drawn:

- stressors for the closed coupled catalyst can be quantified early in the development
- accelerated test procedures were used to determine product life-time at extreme thermal and mechanical load conditions
- the life-time of the substrate depends on outer construction and on matrix type
- robustness is improved with DM and HD design
- the 600-50µm PE Metalit® showed superior emission performance and robustness with the potential to reduce PGM loading level due to minimized thermal inertia.
- SIT component test shows tentative similar robustness performance as achieved in the vehicle endurance test run. More development work is necessary to generate a correlation between component test and vehicle endurance test.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

CC	close coupled catalyst position
DM	Double-Mantel-Design
EoL	End-of-Life
FTP	Federal Test Procedure
HD	High Durable
LS	Longitudinal Foil Structure
PE	Perforated Foil
PGM	Precious Metal Group
PSD	Power Spectral Density
Std	Standard Foil Substrate

SIT	Super-Imposed-Test (thermal and mechanical)
TB	Toe board catalyst position
TS	Transversal Foil Structure
WOT	Wide Open Throttle
cp	Heat Capacity
dT/dt	Temperature Transient
dp	Back Pressure
T	Temperature

REFERENCES

[1] Thomas Nagel, Jan Kramer, A. Schatz, J. Breuer, Ron Salzman, J. Scaparo, A. Montalbano "A New Approach of Accelerated Life Testing for Metallic Catalytic Converters", SAE-Paper 2004-01-0595

[2] Thomas Nagel, Joachim Diringer, 2000, "Minimum test requirements for high cell-density, ultra-thin wall catalyst supports, Part 1", SAE 2000-01-0495

[3] Katrin Schaper, Rolf Brück, Roman Koniezny, Andreas Dietsche, Rainer Zimmer, "New Design of Ultra High Cell Density Metal Substrates", SAE-Paper 2002-01-0353

[4] M. Bollig, J. Liebl, R. Zimmer, M. Kraum, O. Seel, S. Siemund, "Next generation catalysts are turbulent development of support and coating", 2004, SAE-Paper 2004-01-1488

[5] Daniel W. Wendland, Philip L. Sorrell, John E. Krechner, "Sources of Monolith Catalytic Converter Pressure Loss", 1991, SAE-Paper 912372

[6] Clemens Brinkmaier, Christof Schön, Guido Vent, Christan Enderle, "Catalyst Temperature Rise during Deceleration with Fuel Cut", 1991, SAE-Paper 912372