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Substrate Selection for a Diesel Catalyst

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ABSTRACT

A substrate is the supporting material onto which a washcoat and catalyst formulation are applied in a catalytic converter. Four different commercially available diesel exhaust purifiers were tested for durability and resistance to vibration. Each purifier contained a flow-through monolith substrate of different design as well as the necessary packaging elements. A hot vibration test was used to evaluate each sample. This is an accelerated test that consists of passing hot exhaust gases through each purifier while oscillating it longitudinally on a test bench. Tests were conducted for 50 hours or until structural failure of the substrate.

Diesel engines are commonly used in industrial equipment, exposing a catalytic converter in this application to a harsh environment. In practice, we have come across many cases where different substrate designs have failed under such difficult operating conditions. Observed structural failures of substrates in applications such as mining equipment prompted this investigation [1]. The four substrates selected for testing covered differing design elements. Of the four substrates tested, the brazed, s-shaped, metallic design proved to be the most durable.

INTRODUCTION

The operating environment of diesel powered equipment is different from that of spark ignition engines. Diesels are commonly used in industrial equipment that are subject to more shock and vibration than vehicles powered by a spark ignition engine such as with passenger vehicles. Consequently, durability is an important selection criterion when choosing a catalyst substrate for off-highway diesel applications. The amount of backpressure across a substrate is another important criterion for the selection of any catalyst substrate. Higher backpressures will result in diminished engine performance and thus should be avoided. In addition, the substrate-shell assembly, which includes the substrate, the exterior shell or can, and the required packaging elements, should be of a compact design due to space limitations on most equipment. This paper will attempt to evaluate the durability of substrate designs under high vibrational and temperature operating conditions. The hot vibration test was used for this purpose. This test has been used by substrate manufacturers as a means of proving their substrate designs for their customers' spark ignition applications. To reflect the colder exhaust temperatures experienced by diesel applications, the exhaust gas temperature used for this investigation was lower than that used on similar tests done for S.I. applications. No emissions testing was performed.

FUNCTION OF A SUBSTRATE - The function of the substrate is to act as a carrier for the washcoat and for the noble-metal oxidizing catalyst. Cells running axially through the substrate provide small channels through which the exhaust gas flows. For the diesel application, a cell density of 31 cells/cm^2 is common. The washcoat and catalyst coat these narrow channels, exposing the catalyst to the exhaust gases to promote the desired oxidation reactions. Catalyst substrates are sized by volume such that the exhaust gas space velocity does not exceed some predetermined level. Sufficient catalyst to satisfactorily reduce emissions determines this design space velocity.

FAILURE MODES - There are numerous designs of catalyst substrates on the market. All are proven as supports for the applied washcoats and catalysts. Occasionally, these substrates and/or their packaging elements suffer mechanical failure when installed on industrial diesel equipment. Failure modes include fragmentation of the substrate, loosening of the substrate from its shell, and shifting or telescoping of the substrate layers. Fragmentation of the substrate refers to the fracturing of the substrate into two or more pieces. This is a predominant failure mode in ceramic substrates. Thermal stresses resulting from radial and axial temperature gradients are one cause of ceramic substrate fractures. Since diesel exhaust is substantially colder than that of gasoline engines, the thermal fatigue potential is eliminated [2]. Therefore, the mechanical durability of a ceramic substrate is the primary factor affecting total substrate durability for the diesel application. Under a steady load condition, a crack is stable and will not grow if the applied load is below a threshold value. However, a crack can grow if either the stress is cycled or if the environment surrounding the structure is corrosive. For a particular load condition, a fatigue failure occurs when the crack grows to a critical length such that it propagates catastrophically [3]. Another type of failure, the loosening of a substrate from its outer shell occurs when the method of attaching the substrate to the shell fails. This can result from an erosion of the ceramic mat, crushing of the substrate material adjacent to any retaining rings, or from the fracture of a welded or brazed joint. Once a substrate has become loose, it is likely to suffer considerable additional damage from rattling around in its shell. Telescoping or shifting of the substrate layers occurs in a metallic substrate when the attachment method between the layers fails, allowing relative movement between the layers to occur. An audible increase in noise levels provides an early indication of the above failures.

DESCRIPTION OF SUBSTRATE CANDIDATES

The real experiences of substrate failure in diesel applications presents the problem of selecting the most durable design. For this study, diesel exhaust purifiers obtained from four different suppliers were compared and evaluated under controlled high vibrational and temperature conditions. Each purifier contained a substrate of different design and were sized for similar exhaust gas flows.

The purifier designs examined have been chosen to cover differences in two major design elements. These are: (a) substrate or catalyst support
(b) packaging materials

Each substrate design has its own packaging requirements. The packaging materials include all of the parts required to secure and protect the substrate in its outer shell.

DESCRIPTION OF PURIFIER DESIGNS - The four purifiers tested have been labelled samples A, B, C, and D respectively. Each sample consists of many small cells running axially from the inlet to the outlet side. All of the substrates have a cell density of 31 cells/cm^2.

Sample A - Sample A uses a ceramic substrate having cells of square cross-section. The substrate-shell assembly of sample A contains a ceramic mat between the substrate and the protective outer stainless or heat resistant steel-shell. The ceramic mat acts as a shock absorber between the substrate and shell, allows for expansion differences between the outer shell and substrate, provides some thermal insulation, and provides a positive pressure which can hold a cracked substrate together and thus extend its useful life. Support flanges are welded on either side of the substrate to prevent axial movement.

Sample B - Sample B uses a metal substrate. The substrate cells are constructed of alternating layers of flat and corrugated metal foil that produce a trapezoidal cell cross-section. These foils are coiled around a pin at the substrate center to produce a cylindrical shape. The packaging materials used include support flanges and a ceramic mat. Metal pins are shot into the substrate and welded to the outer shell to prevent foil layers from slipping past each other in a telescoping effect.

Sample C - Sample C also uses a metal substrate constructed of alternating flat and corrugated foils. The foils are wrapped around two centers forming the desired S-shaped cross-section. The substrate-shell assembly of sample C has no additional support components as the substrate foils are brazed to each other and directly to the outer shell.

Sample D - The substrate of sample D is constructed of layers of corrugated foil only, producing cells of varying cross-sectional area. These foils are assembled in short variable lengths forming chords across the circular substrate cross-section. This design includes support flanges as well as two stainless or heat resistant steel support sheets of 1.5 mm thickness, placed between foil layers such that the substrate is divided into three sections.

Basic dimensions of the substrate-shell assemblies are listed in Table 1.

Table 1
Basic Purifier Dimensions

Sample	Substrate		Outer Shell		Retainer Ring
	O.D. (mm)	Length (mm)	O.D. (mm)	Length (mm)	I.D. (mm)
A	195	90	202	110.5	184
B	172.5	90	184	94	168
C	174.6	90	178.6	100	N/A
D	182	90	184	94	168

As can be seen from this Table 1, the retainer rings overlap the outermost cell channels of substrates A, B, and D. This overlap plus the close fit of the retainer rings prevents axial motion of the substrate within its shell. (Frictional resistance between the ceramic mat and the substrate also provides resistance to axial movement given sufficient positive pressure provided by the mat). A disadvantage of this design is that the channels in the covered section of the substrate are not exposed to the gas flow. This fraction of the substrate volume is therefore relatively inactive. In samples A, B, and D, this covered section represents a surprising 11.0%, 4.6%, and 14.7% of the total substrate volume respectively.

HOT VIBRATION TEST

The hot shake (or hot vibration) test apparatus consisted of an emission simulator, a cyclic shaking device, and the exhaust piping system to which the four substrates were installed. See Fig. 1.

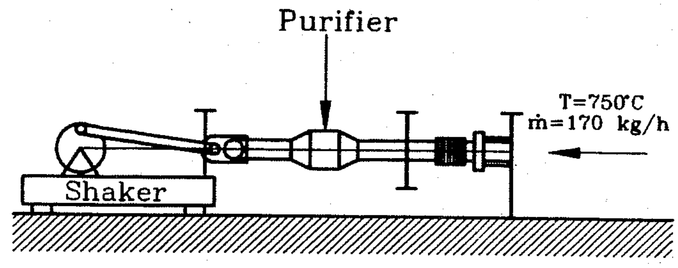

Figure 1.Test Bench Schematic

The hot vibration test has been used extensively for evaluating the durability of substrates for spark ignition automotive applications [4,5,6]. To better reflect the cooler exhaust gas of diesel engines, we used an exhaust gas temperature that was lower than those employed testing substrates for S.I. engines. The chosen gas flow rate was appropriate for the substrate sizes tested. Exhaust gas was produced by the emission simulator having a temperature of 750 C and a mass flow rate of 170 kg/h. The cyclic shaking device produced an axial, sinusoidal oscillation, with an amplitude of ±1.6 mm at a frequency of 80 Hz. For the purposes of the durability test, no evaluation of the emissions reduction was performed. Test conditions for each substrate are listed in Table 2.

Table 2
Durability Test Conditions

Exhaust Gas Temperature Inlet	T_1 = 750 °C
Exhaust Gas Mass Flow	$\dot{m}_g$ = 170 kg/h
Waveform	sinusoidal
Amplitude	s = ±1.6 mm
Frequency	f = 80 Hz
Acceleration Level	a_L = 40 g
Test Duration	t = 50 h
Direction of Simulation	axial

The durability of the substrates was evaluated by their time to failure or the amount of damage incurred after 50 hours. Substrate failure was deemed to have occurred when the observed substrate damage would prevent further operation under real operating conditions. For example, the detaching of the substrate from its shell would require the removal of a catalytic converter from the diesel equipment. This is necessitated by the excessive rattling noise created and to protect the exhaust system from damage. Fragmentation of the substrate will also cause excessive noise, and small fragments can work their way into the muffler. During testing, the substrates were removed from the test bench, examined, and photographed when there was an audible increase in noise levels that suggested substrate damage.

OBSERVATIONS

The durability of the four substrates proved to vary significantly. Sample C was still functioning after the 50-hour test period, while samples A and B had structural failure after less than one hour.

SAMPLE A - After starting the apparatus, the substrate failed after only five minutes. This occurred although the gas temperature had not yet warmed up to test conditions. Most of the substrate damage was centered around the two perpendicular seams where the four pieces of substrate were bonded together. See Fig. 2.

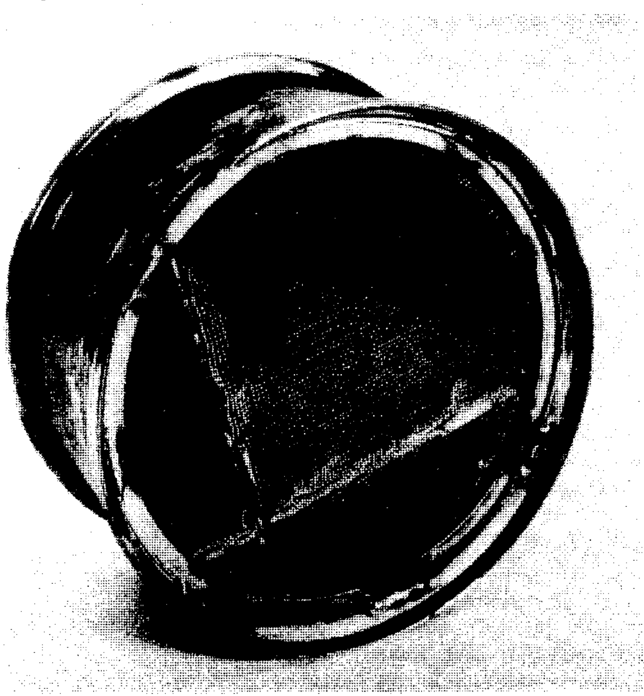

Figure 2. Sample A Damage After 5 Minutes

Much of the bonding material near the inlet and outlet faces had broken away, leaving the four substrate sections loose relative to each other. The smallest piece of substrate shifted about one millimeter downstream of the other sections. The pieces were being held together by the positive pressure generated by the ceramic mat. Along the length of the two seams, pieces of the ceramic substrate had broken away. The largest resulting cavity measured 60mm long by 19mm wide. There was also substrate damage where it had contacted the substrate retainer rings. Below the retainer rings, about 4mm of the substrate material had been crushed and eroded away. See Fig. 3.

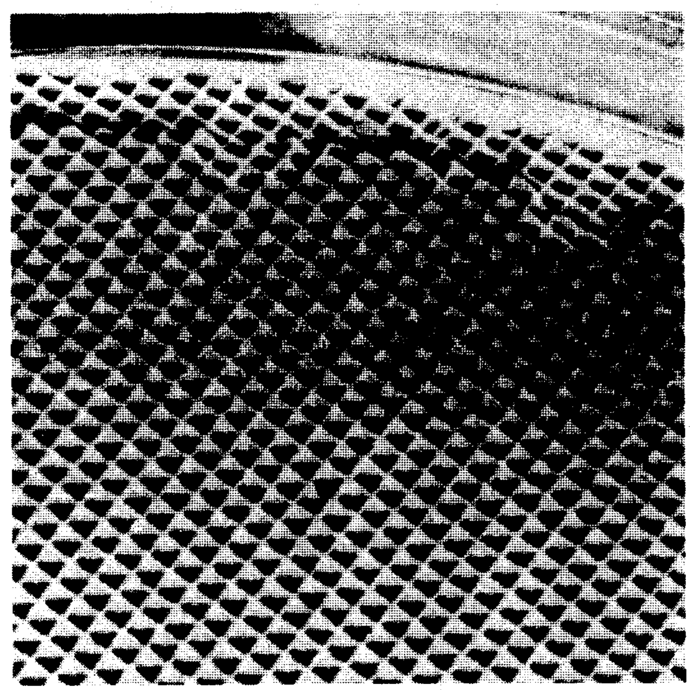

Figure 3. Sample A Substrate Erosion Below Retainer Rings

When the substrate was removed from the test bench, ceramic fragments were found in both the inlet and outlet cones.

SAMPLE B - After one hour, the substrate was removed. The ceramic mat had completely eroded away leaving the substrate completely detached from its shell. The foils near the outer perimeter of the substrate had begun to slip past one another in a telescoping effect. See Fig. 4.

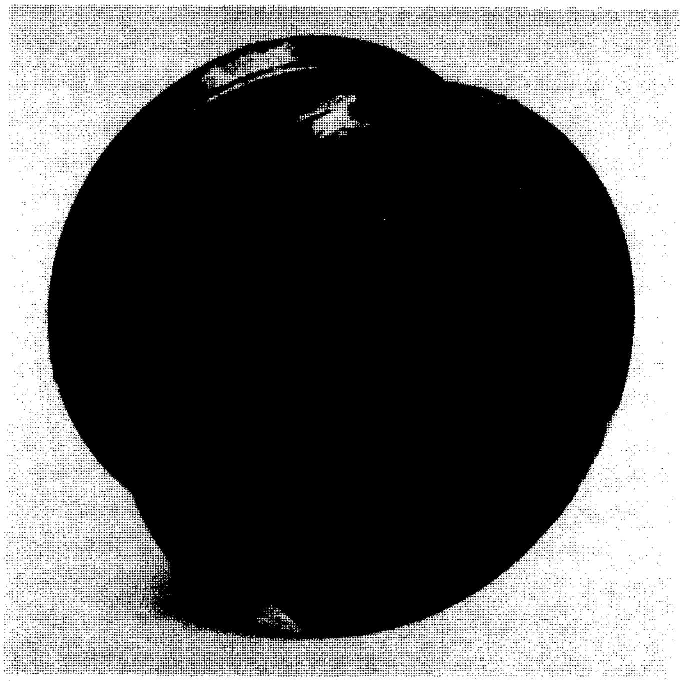

Figure 4. Telescoping of Substrate B After 1 Hour

Also, two of the layers closer to the center axis of the substrate had also slipped past one another by about one millimeter in the axial direction. See Fig. 5.

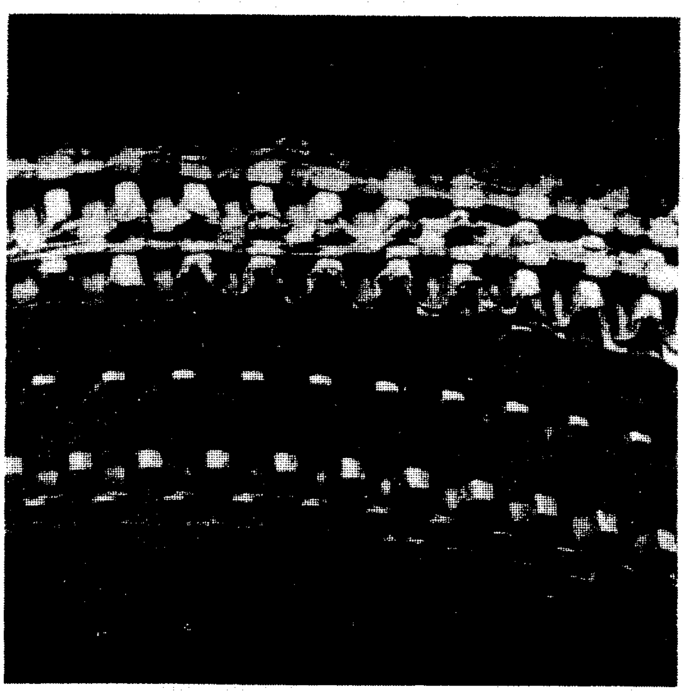

Figure 5. Slippage of Foil Layers in Sample B

SAMPLE C - After 50 hours, the substrate showed no damage or separation from its shell. See Fig. 6 and 7. In addition, no increase in noise levels that would suggest substrate damage was present.

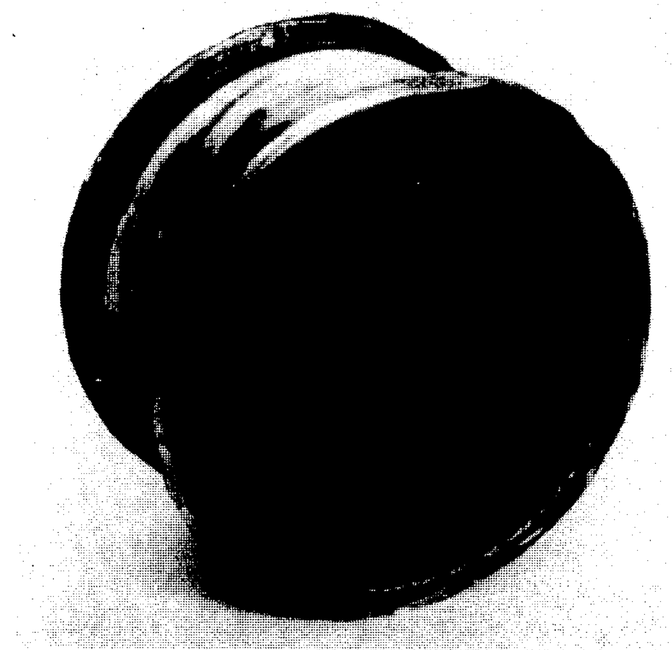

Figure 6. Sample C - No Damage After 50 Hours

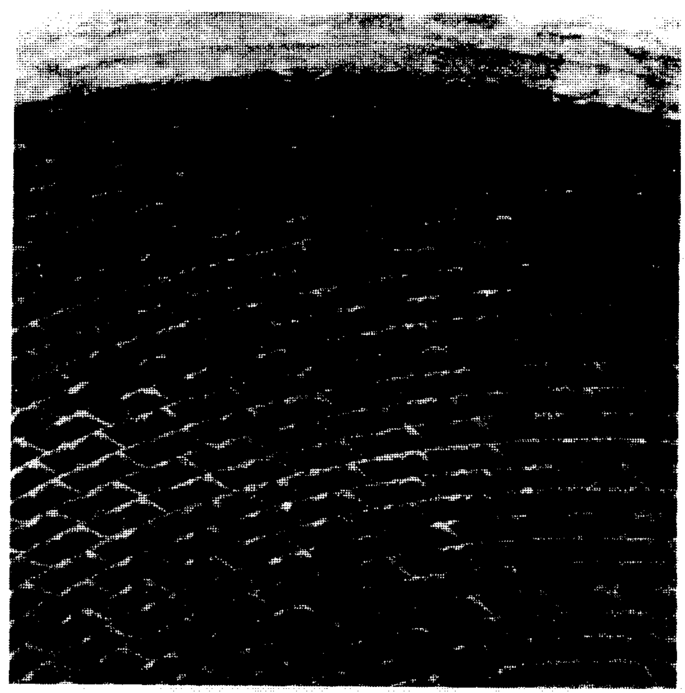

Figure 7. Sample C After 50 Hours: Detail

SAMPLE D - After 12 hours, the corrugated foil layers had shifted slightly, both in the axial direction, and sideways. Otherwise, the substrate appeared mechanically sound, so testing was continued. After 49.4 hours, the shift between corrugated layers had become more pronounced, especially in the axial direction. The thin foil layers had been crushed by a depth of about 8 mm beneath the retaining rings, reducing the ability of the rings to provide axial support. See Fig. 8

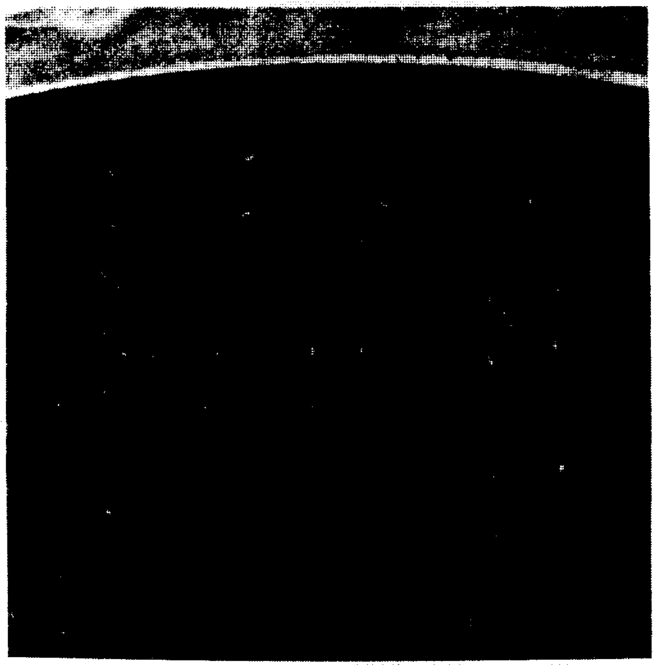

Figure 8. Sample D Foil Layers Shown Crushed Below Retainer Rings After 49.4 Hours

The layers of foil had become loose such that they could be easily pushed past each other by hand. The steel support sheets had also become slightly bent at the ends. See Fig. 9.

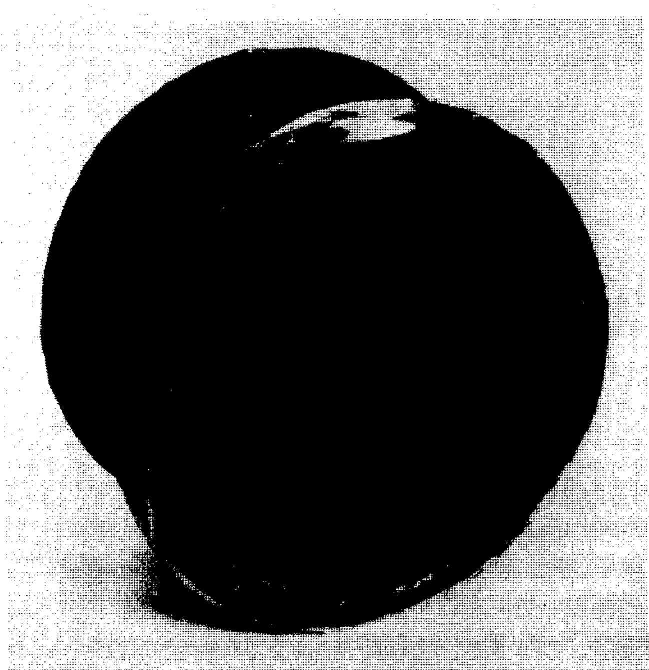

Figure 9. Substrate D Damage After 49.4 Hours

DISCUSSION OF DESIGN ELEMENTS

From the test results, the metallic substrates proved to be more durable than the ceramic. This suggests that the use of a metallic substrate would be desirable in heavy-duty diesel applications. With the metallic substrate of sample B, the alternating flat and corrugated foils wrapped around a single center produce a relatively long unsupported length of foil relative to the substrate size. The only support between the different coil layers are the metal pins driven through the layers to restrict axial movement. However, under the test conditions, the pins tore open progressively larger holes in the foil layers until the pins could no longer prevent the telescoping of the substrate.

The short corrugated lengths of design D, had a much shorter unsupported length than design B. These short lengths of foil supported at both ends were better able to resist damage under the test conditions. These foils did eventually become crushed between the retaining rings, thus loosening the substrate layers. The slippage between the corrugated foil layers resulted in the formation of some smaller cell channels. Cell channels that are too small are undesirable because they are more likely to become clogged with soot particles. The use of flanges to prevent axial movement covers the outermost cell channels, making them under-utilized. In addition, the amount of open area of the substrate for a given outer shell diameter is reduced by the area covered by the support flanges.

The brazed substrate design of sample C performed the best under test conditions. During the fifty-hour test period, there was no audible increase in noise levels that would suggest substrate damage. After removal from the test bench, there was also no visible damage. This design had no packaging material allowing for a compact outer shell diameter relative to the substrate matrix diameter. The design also required no support flanges or pins that could restrict gas flow or cover the outermost cell channels.

SUMMARY AND CONCLUSIONS

Sample C, the brazed metallic substrate design, was the most durable under the test conditions. Using the criteria of choosing the most durable substrate design, our test found this design to be the best for use as a diesel catalyst. Other considerations in selecting the brazed metallic substrate are as follows:

1 This design required no flanges or pins that could act as restrictions to gas flow or create under-utilized cell channels in the substrate perimeter.

2 No packaging material that would require a larger outer-shell diameter was needed, thus allowing for a more compact purifier design for a given exhaust gas space velocity.

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