TABLE 19.7
Axial Thermal Shock Parameter for Cordierite Ceramic and SiC Diesel Particulate Filters (for $T_p = 294°C$)

Temp. (°C)	EX-80 (100/17)	EX-80 (200/12)	SiC (200/18)
600	4.2	3.9	0.6
700	2.4	2.2	0.4
800	1.5	1.4	0.3
900	1.1	1.0	0.25
1000	0.8	0.75	0.20

From Miwa, S., SAE 2001 World Congress, Detroit, MI, March 2001, 2001-01-0192. Courtesy of SAE.

In the above equation T_c and T_p denote the temperature of center and peripheral regions of the filter during regeneration and α_c and α_p denote the corresponding CTE values. In view of the conical inlet pipe near the peripheral region, there is less gas flow in that region and the temperature T_p is typically 400°C. The center temperature, however, is higher depending on soot loading, O_2 content, and flow distribution. We will assume T_c to range from 600°C (low soot loading) to 1000°C (high soot loading) and compute TSP values for each of these T_c values while keeping $T_p = 400°C$. The results of this exercise are summarized in Table 19.7.

Let us note that the TSP values for EX-80 filters are 400 to 700% higher than those for SiC filters due, primarily, to their very low CTE values. The higher TSP value signifies improved thermal shock resistance and extended thermal durability. Alternatively, it permits higher regeneration stresses without impairing the filter's durability. It should be pointed out that Equation (19.19) does not account for 10 times higher thermal conductivity of SiC which will result in higher T_p and higher TSP values. Hence both EX-80 and SiC filters will approach comparable thermal shock resistance, notably at higher regeneration temperatures.

The power law fatigue model [78,79] helps estimate the safe allowable regeneration stress for a specified filter life. Denoting the filter's short-term modulus of rupture by S_2, the safe allowable stress S_1 is given by

$$S_1 = S_2\left(\frac{t_2}{t_1}\right)^{1/n} \tag{19.20}$$

where t_1 denotes the specified filter life, t_2 denotes equivalent static time for measuring short-term modulus of rupture, and n denotes the dynamic fatigue constant of filter composition. The latter is obtained by measuring MOR as function of stress rate at temperature T_p. For a conservative estimate of S_1, the lowest value of n should be used in Equation (19.20). The equivalent static time t_1 is defined as the actual test duration for measuring MOR divided by $(n+1)$. Since the typical test duration is 30 sec and the lowest value of n is approximately 29 [61], $t_1 \cong 30/30 \cong 1$ sec. Filter life is generally specified in terms of the number of regeneration cycles over the vehicle's lifetime. We will assume a filter life of 250,000 km with a regeneration interval of 450 km and regeneration duration of 10 min. This translates to $t_1 = 6000$ min $= 360{,}000$ sec. Substituting these values in Equation (19.20), we arrive at a safe allowable stress of 1.7 MPa or 60% of MOR value in axial direction. This superiority of the EX-80 filter derives from its higher fatigue constant and MOR value, which, in turn, are related to its optimized microstructure. The effect of filter size, relative to test specimen, may reduce the allowable stress to 30% of MOR value.

19.5.3 Mechanical Durability

The mechanical durability of a ceramic filter depends not only on its tensile and compressive strengths but also on its packaging design [70]. In addition to mechanical stresses due to handling and processing, the filter package must be capable of withstanding in-service stresses induced by gas pulsation, chassis vibration, and road shocks. The design of a robust packaging system for catalyst supports discussed in Section 19.2 is equally applicable to the filter. Table 19.6 demonstrates more than adequate strength for tourniquet canning which is recommended for long-term mechanical durability. In addition, preheat treatment of intumescent mat also promotes mechanical durability [80].

19.6 ADVANCES IN DIESEL FILTERS

Both the stringent diesel emission legislation in Japan, North America, and Europe (to be introduced in 2007) and the popularity of diesel passenger cars in Europe have led to new advances in diesel filter technology. With new legislation in the offing one of the automotive manufacturers in Europe (PSA) decided to introduce a noncordierite DPF in MY 2001 diesel passenger cars [24,64]. This created a great opportunity for new filter materials [25,62–65], new filter designs [64,81], and improved detection techniques for soot deposits through increased pressure drop [82]. The motivation for developing new materials stemmed from the need for higher thermal conductivity, higher melting temperature, and higher heat capacity than those of cordierite ceramic to facilitate regeneration under uncontrolled conditions [62].

Uncontrolled regeneration is most often described as an unplanned regeneration in which the combustion of a large amount of accumulated soot occurs under conditions in which the exhaust gas has a low flow rate but high oxygen content, resulting in temperatures that far exceed those of controlled regeneration. For example, operation of a diesel engine at high loads and speeds could produce exhaust temperatures that are sufficiently high to initiate combustion in a filter that is heavily loaded with soot. If the engine were to continue running at these conditions throughout combustion, the low oxygen content of the exhaust gas would result in slow burn, while the higher flow rate of the exhaust would serve effectively to transfer heat away from the filter. Thus, only moderately high regeneration temperatures would be achieved. However, if the engine load were to be dramatically reduced soon after combustion was initiated, such as might occur under near idling conditions, then the exhaust flow rate would decrease and the oxygen content of the exhaust gas would increase. The increased oxygen content would accelerate soot combustion, while the lower exhaust flow rate would be less effective in removing heat from the system to cool the filter. Consequently, excessively high temperatures could be achieved within the filter during this uncontrolled regeneration, potentially causing cracking or melting of the filter.

Similarly, the motivation for new designs stemmed from the need for reducing thermal stresses during uncontrolled regeneration by either limiting the peak regeneration temperature to 1000°C via higher heat capacity [81] or by incorporating stress-relief slits in the filter albeit at the risk of impairing mechanical integrity [64]. In this section, we compare new materials like improved cordierite RC and SiC with the standard cordierite. We then discuss new filter designs and how such designs impact their performance including pressure drop.

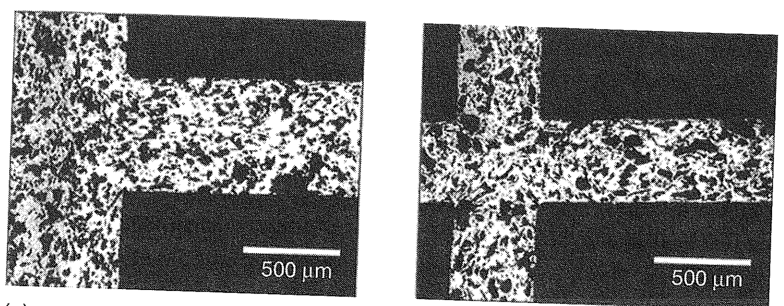
19.6.1 Improved Cordierite "RC 200/19" Filter

Because there is no known compositional modification that can be made from a cordierite-based ceramic to increase its refractoriness without also increasing its CTE and compromising its thermal shock resistance, survival of a cordierite filter must rely on modifications in filter design that reduce the maximum temperature the filter will experience during uncontrolled regeneration.

The temperature increase experienced by the filter during a regeneration is inversely proportional to the heat capacity of the filter per unit volume for a given exhaust gas flow rate and soot mass burned per unit volume. The volumetric heat capacity of the filter is equal to the product of the bulk density of the filter and the specific heat of the ceramic comprising the filter. Thus, the temperature increase during regeneration can be reduced simply by increasing the mass per unit volume of cordierite filter [81]. An increase in filter mass per unit volume may be achieved by increasing the filter cell density (cells per unit area) or wall thickness, or decreasing the percent porosity of the filter walls. However, changes in cell geometry or porosity will also have an effect on the pressure drop across the filter. An increase in cell density decreases the pressure drop by virtue of higher geometric surface area while an increase in wall thickness increases the pressure drop due to the increased path length through the wall. Increases in wall thickness are generally limited by the permeability of the ceramic comprising the wall. A decrease in porosity may increase the pressure drop unless the effect can be offset by simultaneous modification of the pore size or pore connectivity.

Development of a cordierite ceramic that exhibits a reduced soot-loaded pressure drop for a given filter geometry, cell density, and wall thickness requires modification of the pore microstructure of the ceramic. This may be achieved, for example, by a change in raw materials, forming parameters, or firing conditions (such as furnace atmosphere, heating rates, peak temperature, and hold time at peak temperature). The best candidate resulting from such modifications was designated "RC filter" with a cell structure of 200/19 [25]. Table 19.6 compares its properties with those of EX-80, 100/17, cordierite filter. Figure 19.15 compares the pore microstructure of EX-80, 100/17 and RC 200/19 filters.

It is clear from these data that the RC 200/19 filter offers 25% higher filtration area, 84% higher wall permeability, 52% higher weight density, and 52% higher heat capacity. The latter helps reduce the peak temperature of the RC 200/19 filter during uncontrolled regeneration thereby compensating for its slightly higher CTE value relative to that of the EX-80, 100/17 filter. Furthermore, both the larger filtration area and higher wall permeability of the RC 200/19 filter should result in a more uniform soot distribution and lower temperature gradient thereby preserving or improving its thermal shock resistance as shown later.



(a) (b)

FIGURE 19.15 Scanning electron micrographs of polished section of (a) RC 200/19 filter wall and (b) EX-80, 100/17 filter wall showing improved pore connectivity of the RC 200/19 filter.

19.6.2 SiC Filters

As noted at the beginning of this section, the European automaker PSA introduced a SiC filter in MY 2001 diesel passenger cars due to its high thermal conductivity. Table 19.6 compares the properties of cordierite ceramic, RC 200/19 and SiC 200/18 filters. The latter is a cement-assembled commercial silicon carbide filter from Ibiden. It should be noted that EX-80 cordierite has the lowest intrinsic material density. Moreover, when the specific heat and density of the filter are combined, the heat capacity of the cordierite filter turns out to be lower than that of the SiC filter. A lower heat capacity filter can be heated quickly, resulting in faster regenerations. Faster regeneration generally means lower regeneration fuel penalty if raw fuel injection or additional engine power are required to produce sufficient heat to initiate regular regeneration. While a high heat capacity filter may be desirable for uncontrolled regeneration (to soak up excess heat), a high heat capacity also makes it more difficult to heat the filter for regular controlled regeneration.

Thus, the salient issue comes down to balancing heat capacity of the filter with the material melting point and ash reaction temperature such that the filter regenerates quickly and efficiently during controlled regeneration while still having a sufficiently high melting point and/or ash reaction temperature to prevent pin holes and catastrophic failure during uncontrolled regeneration.

The thermal conductivity of cordierite (<2 W/m/K) is much lower than that of SiC ($\sim$20 W/m/K at 500°C). The thermal conductivity for all these materials drops as the temperature increases, such that their conductivity at $\sim$1300°C is half that at 500°C. The value of a high thermal conductivity material is a matter of some debate, as the cooling effect due to high gas flow through the substrate takes heat away from the hot spot much faster than the conductivity can draw the heat away from the hot spot.

The differences in thermal expansion coefficient, E-modulus, and strength among the three materials translate into different thermal shock index (TSI) defined by (MOR/E.CTE). Specifically, the very low CTE and low E-modulus of cordierite materials result in a very high TSI value. This is significant, as cordierite is well known for its excellent thermal shock properties. Despite the high strength of silicon carbide, its high CTE and high elastic modulus lead to a rather low TSI (<200). The segmentation of the commercial SiC may represent an effort to limit the distance over which thermal stresses can build.

19.6.3 New Filter Designs

As noted earlier, one way to improve a filter's thermal durability is to reduce the peak regeneration temperature by increasing its thermal mass or heat capacity. This is most readily done by modifying the cell design, e.g., by increasing the cell density and wall thickness simultaneously. A series of regeneration tests were conducted on 2 in diameter × 6 in long (5.08 cm × 15.24 cm) EX-80 filters, with different cell designs, loaded with 9.6 g/l of soot and the peak regeneration temperature was measured as function of the filter's weight or heat capacity [80]. These data, summarized in Figure 19.16, demonstrate that the peak temperature can be reduced by several hundred degrees by increasing the heat capacity via filter weight. A similar reduction in peak regeneration temperature was observed for the RC 200/19 filter whose heat capacity is 20% higher than that of the EX-80, 100/17 filter (see Figure 19.17) [25].

Another approach to improving thermal durability is to introduce stress-relief slits in the center region of filter, which can reduce thermal stresses by 20 to 70% depending on slit dimensions and location as shown in Figure 19.18 [64]. Of course, these slits must be filled with sealing material to prevent soot-laden exhaust gas from escaping. Regeneration tests on cordierite, SiC, and Si/SiC filters verified that both the improved material properties of the

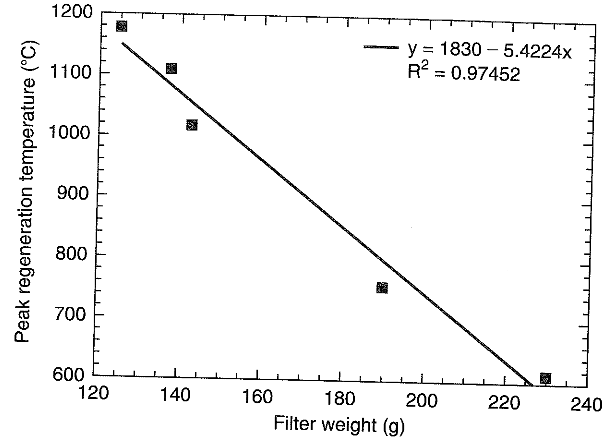


FIGURE 19.16 Effect of filter weight on peak regeneration temperature.

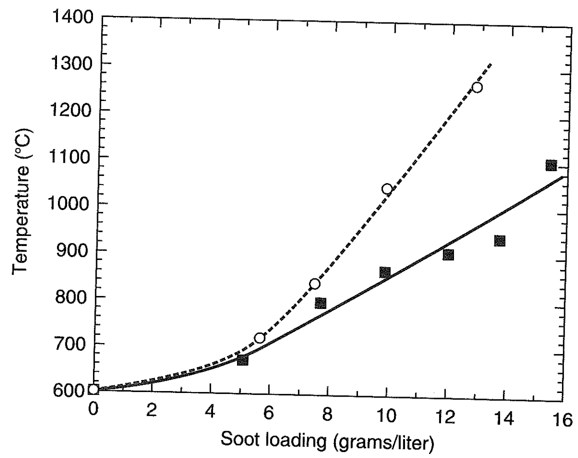


FIGURE 19.17 Maximum temperature in 14.4 cm × 15 cm filters of RC 200/19 (■) and EX-80, 100/17 (○) during uncontrolled regeneration versus soot loading.

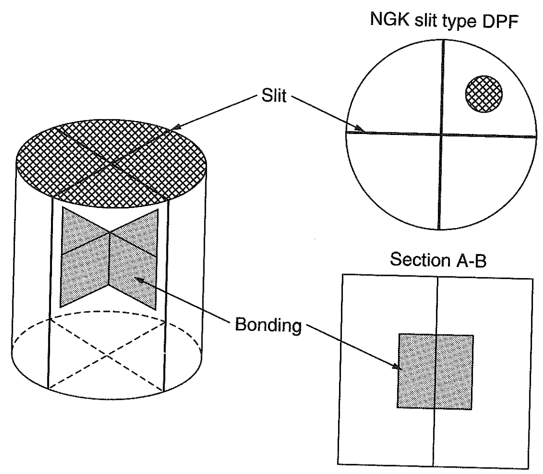


FIGURE 19.18 Filter design with stress-relief slits.

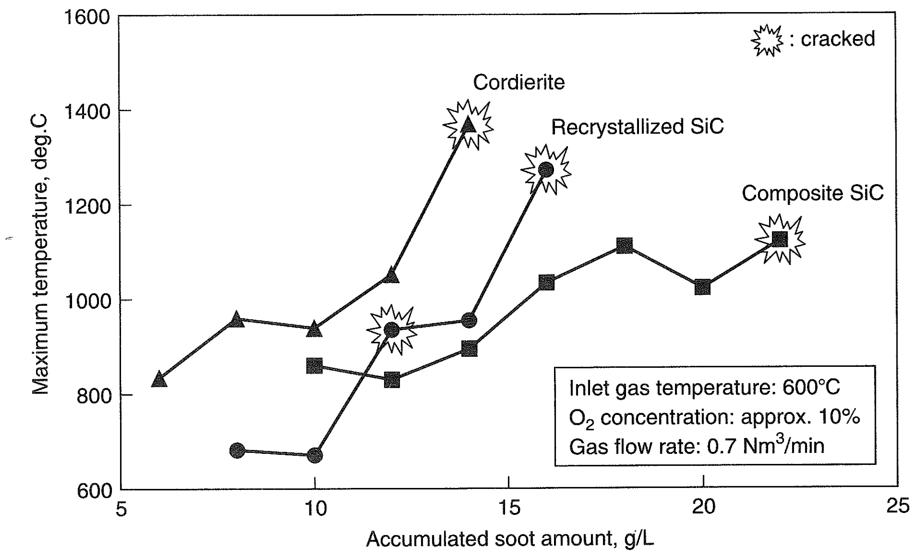


FIGURE 19.19 Maximum regeneration temperature versus soot loading for three different filters with and without stress-relief slits.

Si/SiC filter and the presence of stress-relief slits helped increase the failure temperature from 900°C (for SiC) to 1100°C with soot loading as high as 22 g/l (see Figure 19.19).

The design approach can also be used to reduce the pressure drop across the filter by increasing its diameter/length ratio while preserving the required filter volume and filtration area [81].

19.7 APPLICATIONS

19.7.1 CATALYTICALLY INDUCED REGENERATED TRAP

In the early 2000s PSA Peugeot Citroën introduced a particulate filter system on passenger cars, in which an integrated fuel additive system was applied [83]. This PSA system can be operated with diesel fuel containing up to 500 ppm sulfur. Currently more than 500,000 units are on the market (winter 2003). Their particulate filter system (see Figure 19.20) includes:

1. A filter medium made of silicon carbide with temperature and pressure sensors.
2. An integrated fuel additive system that injects the required quantities of the cerium based catalyst (Eolys™ from Rhodia Terres Rares) whenever the fuel tank is refilled.
3. Common-rail HDI engine monitoring and control software to control filter regeneration and self-diagnosis of the filter.

The pressure sensor monitors filter clogging, and the engine computer initiates the regeneration when necessary. The regeneration involves postcombustion, raising the exhaust fumes to 450°C at the filter inlet. A complete regeneration only requires two to three minutes and is performed every 400 to 500 km without the driver noticing. The cerium-based catalyst additive is dissolved in a solution of 5 g cerium per 100 ml. It is injected into the fuel tank to give the diesel a content of cerium of approximately 25 ppm by weight. The 5 l tank of