

Appendix D

Technical Support Document

A. Need for a Separate Aftermarket Diesel Particulate Filter (DPF) Procedure

ARB has existing aftermarket programs for catalytic converters and emission critical parts for highway motorcycles. However, the evaluation procedures developed to support these programs are neither adequate nor appropriate for aftermarket DPFs due to the extreme differences in engine and emission control technologies.

1. Technological Differences between DPFs and Catalytic Converters

The proposed procedure is needed because of the technological differences between DPFs and catalytic converters, and between diesel and gasoline engines. The already established procedure used to evaluate aftermarket catalytic converters is not appropriate for evaluating DPFs.

a. Gasoline vs. Diesel Engine technology

Gasoline engines, favored in the United States for light-duty vehicles such as passenger cars, are spark-ignition engines. For conventional multi-point fuel injection (MPFI) gasoline vehicles, fuel is first mixed with air at or near a stoichiometric (chemically balanced) ratio, then compressed by pistons in the combustion chamber, and then ignited by sparks generated by spark plugs. For most recent gasoline direct injection (GDI) vehicles, fuel is highly pressurized, and injected via a common rail fuel line directly into the combustion chamber of each cylinder, as opposed to conventional multi-point fuel injection that injects fuel into the intake tract, or cylinder port. The primary pollutants emitted by a gasoline engine are products of the incomplete combustion of the fuel (carbon monoxide, CO, and unburned hydrocarbons, HC) and oxides of nitrogen (NOx), which is generated by the compression of the intake air. A catalytic converter is used as an exhaust aftertreatment to reduce the levels of these emissions. Because the air/fuel mixture is fairly homogeneous, little particulate matter (PM) is produced from conventional MPFI gasoline engines. However, it is likely to increase the particulate mass emissions from the GDI vehicles.

Diesel engines, favored for heavy-duty applications due to their torque and fuel efficiency, are compression ignition engines, which operate by compressing the air first and then injecting the fuel into the combustion chamber. Due to thermodynamics, the air compression raises the temperature of the air and the fuel vaporizes as it mixes with the hot air. When the fuel vapor reaches its auto-ignition temperature, it ignites without the need for a spark plug (although a glow plug may be used to start cold engines). Diesel engines also use a much higher air/fuel ratio than gasoline engines. This method of mixing excess, compressed air and fuel leads to a heterogeneous mixture in the combustion chamber which, in turn, leads to the formation of much more PM than from the gasoline engines. Higher NOx emissions are generated by diesel engines in comparison to gasoline engines, due to the higher air/fuel ratio. CO and HC are emitted

from diesels as well, though the HC is produced at a lower rate than in gasoline engines, as the heterogeneous mixing in the combustion chamber leads to additional combustion of the unburned HC.

Diesel PM has been classified as TAC in California, as discussed in the ISOR, so aftertreatment of the exhaust by DPFs are needed to reduce the levels of PM emissions. Other technologies have been developed to reduce emissions of other pollutants, such as NO_x, but this proposal does not include them. In addition, diesel engine components must be built to endure higher pressures and temperatures than gasoline engines. A DPF evaluation procedure, thus, must be designed specifically to evaluate diesel emission control devices.

b. Catalyst vs. DPF Technology

Catalytic converters are catalyst-containing, flow-through devices that are well suited for controlling gaseous pollutants emitted from gasoline engines. The modern three-way catalytic converter (TWC) currently in use utilizes three platinum group metals (PGMs), platinum, palladium, and rhodium, to treat the exhaust emissions. The TWC uses a ceramic or metal substrate onto which the PGMs are applied. The exhaust flows through this structure and reacts with the PGMs. NO_x emissions are reduced by converting nitric oxide (NO) and nitrogen dioxide (NO₂) into nitrogen (N₂) and oxygen (O₂) gases. Unburned HC and CO are oxidized into carbon dioxide (CO₂) and water vapor (H₂O). Catalytic converters are flow-through devices and usually do not cause an increase in exhaust backpressure that can strangle engine performance. Under certain circumstances, a partially plugged catalytic converter will create a restriction in the exhaust system.

Wall-flow DPFs are high-efficiency filters that trap PM emitted from the diesel engine and remove it from the exhaust stream. They are composed of a core, which is typically made of an inert substrate, such as cordierite or silicon carbide or other material, which is contained in a steel container, usually referred to as a can. Some DPFs also have a metallic washcoat that acts as a catalyst to facilitate regeneration, as explained, below. Some cores are made of metal-ceramic substrates, such as aluminum titanate, which have unique operational concerns such that manufacturing a truly equivalent aftermarket part would be problematic, as well as staff's ability to evaluate it for that equivalency. In addition, if the cores are made of metal substrates, they have unique safety concerns. Therefore, metal and metal-ceramic cores are not included in this exemption process.

The DPF core has many channels through which the exhaust flows. Alternate channels are plugged in order to force the gas through the filter material, trapping the PM as soot. Hence, DPFs are not flow-through devices, as are catalytic converters. This trapped soot builds up over time, increasing the backpressure as a result, as the engine continues operation. Eventually, the filter must undergo a regeneration to burn off the built-up soot and restore the filter to optimal operating conditions. If regeneration is not regularly or successfully performed, the filter may plug from too much soot and/or it may

go into an uncontrolled regeneration, possibly damaging the filter and surrounding components. Filter regeneration is crucial to the successful operation of a DPF. Warning lights for the operator are triggered if regeneration is not performed accordingly. The engine power may even be de-rated if these warnings are ignored during the engine operation. Original equipment manufacturers (OEMs) use various control strategies to monitor and determine when regeneration needs to be performed.

Most OEM DPFs are catalyzed in order to facilitate regeneration and prevent hydrocarbon slip during DPF regeneration. The catalyst lowers the exhaust temperature needed for oxidation and removal of the soot from 550-650°C to 300-400°C¹, a temperature range that is easier to realistically achieve in certain engine operations. Under high engine loads, the exhaust temperature is sufficiently high that the filter can regenerate passively, with no additional input needed. Under light engine loads or due to lower exhaust gas temperature with EGR, active regeneration is initiated by raising the exhaust gas temperature to 500°C through means such as fuel injection. Catalyzed OEM filters are designed to be used with a mix of passive and active regeneration depending on the actual engine duty cycles. Uncatalyzed DPFs must rely on active regeneration.

Filter regeneration is important not only for continuing smooth performance of the filter in the field, but also for evaluating the durability of an modified part that will undergo periodic regeneration events like the OEM DPF. The high temperatures involved in filter regeneration place significant stress on the filter, which it must be able to withstand. Staff's proposed testing includes an accelerated aging cycle, which will account for sources of deterioration and stress on the filter to assess DPF durability. The accelerated aging cycle developed for catalytic converters does not account for these additional factors unique to DPFs (e.g., DPF regeneration). The proposed durability testing in combination with field compatibility testing and emission testing will indicate how well the modified part will perform in actual use and if it is no less effective in controlling emissions as the OEM DPF, as required by California Vehicle Code (VC) 27156.

Although both may use catalysts, catalytic converters are flow-through devices, whereas DPFs act as PM traps. Therefore, it is not possible to simply apply the existing catalytic converter procedure directly to DPFs. Gasoline engines and diesel engines have different emission concerns due to differences in how these two internal combustion engines operate in terms of converting fuel (via combustion) into mechanical work (vehicle motion). These differences in operation consequently result in differences in the types of emissions that need to be controlled and the emission control devices used. DPF structure can vary widely, including different substrates, washcoats, pore size, etc., thus requiring an evaluation procedure that will ensure that only those modified parts that are equivalent in structure and function will be approved.

¹ Ecopoint, Inc. 2005. *Catalyzed Diesel Filters*. https://www.dieselnet.com/tech/dpf_cat.php. Last accessed April 15, 2015.

2. Modified Part Impact on Emissions

It is important to consider how the modified part will impact engine emissions. The modified part is taking the place of the OEM DPF in these 2007-2009 engines and thus must be just as functional, with real and durable emission reductions. In other words, it must perform as well as, or as effectively and durably as, the OEM DPF in controlling diesel emissions with certain period. In order to address such comparable performance by the modified part on the emission control, the proposed Procedure requires that the modified part must be evaluated in the following categories:

- Filtration Efficiency
- Catalytic Performance
- Thermal Stability
- Emissions Compliance
- Durability

As mentioned in previous sections, wall-flow DPFs are high-efficiency filters that trap PM emitted from the diesel engine and remove it from the exhaust stream. The DPF filtration efficiency is an important characteristic. The proposed Procedure requires the modified part to prove its durable filtration efficiency through emission testing of a degreened, lab-aged and field-aged modified part.

The DPF catalytic performance is a key for successful DPF regeneration and preventing HC and CO slips during the regeneration. The proposed Procedure requires the modified part to prove its catalytic performance not only through a catalytic activity assessment (through NO₂ check or soot accumulation check) that compares the OEM DPF and modified part during a degreening period, but also through proving emission compliance after an accelerated aging period and field demonstration. The DPF catalytic parameters must be as effective and durable as the OEM DPF.

The 2007-2009 heavy-duty diesel engines equipped with DPFs will undergo periodic high temperature operation to fully regenerate the DPF. The high temperature exposure may increase the risks of DPF thermal damage and catalyst deterioration. In addition, lubricant oil exposure is a major source of catalyst poisoning and deterioration. This Proposed procedure delineates a laboratory accelerated aging protocol to simulate not only the high temperature exposure but also the lubricant oil exposure. The proposed laboratory accelerated aging protocol uses a higher active regeneration temperature (700°C) than the average active regeneration temperature experienced in the field to simulate longer field DPF operation time. The details about the laboratory accelerated aging protocol including the lubricant oil exposure are in the proposed Procedure (Appendices 2, 3 and 4) and in Sections C.2.d and C.2.e of this document.

For emission compliance, this procedure requires emission testing of the degreened, laboratory-aged, modified part to ensure that the modified part is in compliance with emission certification standards and is functioning similarly to the OEM DPF even after the modified part has undergone accelerated aging. Emission testing is again performed after the field service accumulation period to confirm the modified part is still functional and effective in emission control.

Diesel engines can vary, including having different horsepowers and displacements, with different calibrations, thus requiring an evaluation procedure that will ensure that only those modified parts that are equivalent in function and appropriate for the engine for which they are intended, will be approved.

3. Modified Part Impact on OEM Engine/System

It is equally important to consider how the modified part is impacting the OEM engine and system. The OEM engine and DPF are certified as part of a complete system. The modified part would be taking the place of the OEM DPF, so the modified part must be compatible and fully integrated with the engine. This compatibility assessment is important to ensure the engine maintains expected backpressure, appropriate DPF regeneration, and does not trigger engine control unit (ECU) fault or error codes.

As mentioned in previous sections, the trapped soot in the wall-flow DPF builds up over time, increasing the backpressure on the engine as it continues to operate. Operating the engine at excessive backpressure for extended periods will impact engine performance and eventually cause engine damage. Therefore the soot accumulation rate for the modified part must be similar to the OEM DPF. If the modified part accumulates soot faster, this would have an impact on engine operation and/or regeneration frequency. Frequent regeneration will increase the fuel consumption and risks of DPF failures. This Procedure requires tests for comparing the soot accumulation rates and backpressure changes of the modified part to the OEM DPF. Additional backpressure comparisons are required during the emission testing of the degreened DPF, lab-aged DPF, and field-aged DPF.

Regeneration is a critical for maintaining optimal DPF performance, as regeneration is controlled by the OEM ECU. To demonstrate this, the proposed Procedure requires at least three field trials on different engines with the modified part installed. It must not negatively impact engine durability or functionality, cause engine damage, alter engine behavior, or trigger any fault warnings or codes during operation.

DPF regeneration methods vary, thus requiring an evaluation procedure that will ensure that only those modified parts that are equivalent in structure and function, and appropriate for the engine for which they are intended, will be approved.

4. Safety Issues

Because of the unique characters of wall-flow DPFs described in previous sections, it is necessary to develop robust procedures appropriate to the specific needs and concerns of DPFs. The proposed Procedure specifically includes requirements that the modified part must meet all applicable safety standards during the design and installation of the DPF. OEMs considered safety in the design and installation of the OEM DPF. Therefore, it follows that the modified part must be designed and installed with the same considerations in mind in order to protect the end user, engine, and vehicle.

5. End-User Protection

In addition to addressing safety concerns, the Procedure includes a number of other provisions for protecting the end user who purchases these modified parts. The proposed regulation requires that the product be warranted to be free from defects for a period of two years from the date of installation. Additionally, installers would be required to provide an installation warranty for a period of two years from the date of installation. Modified parts may be subject to audit testing to check for compliance with the proposed procedures. Additionally, a modified part may be subject to recall if a review of the warranty report, an enforcement case, audit testing, quality control, or any other information demonstrates that a modified part has the potential to: experience catastrophic failure or other safety-related failure; has valid warranty claims in excess of four percent; has caused engine issues or other parts to fail on the engine; has failed quality control procedures; has had a substantial number of units experience a failure of an operational feature; or has not resolved warranty claims within 30 days. These provisions are necessary to ensure that the end user is adequately protected if they choose to replace their OEM DPF with an aftermarket DPF.

B. Elements of the Evaluation Procedure (Procedure)

1. Emission Control Group (ECG)

In order to evaluate a diverse set of aftermarket DPFs for use with a highly varied in-use diesel truck fleet, ARB is categorizing these aftermarket DPFs in a practical and flexible manner. Staff developed a new system that uses basic, control strategy significant parameters of both the engine and application to create “emission control groups.” The parameters depend on the nature of the aftertreatment technologies and compatibilities with the OEM engines. This approach is essential due to the potentially diverse aftermarket DPFs which may be evaluated using this Procedure.

The ECG is a group of like engines and applications from the perspective of how the modified part will interact with the engines and how the engines will interact with the modified part. ARB assessed the OEM engines and aftertreatment configurations for 2007-2009 model years to identify seven major emission control groups based on OEM engine manufacturer, OEM market share, and aftertreatment configuration. The ECG may consist only of engines from a single engine manufacturer, or group of manufacturers, as specified in the Procedure. Categorizing the engines by ECG instead of on an engine family number (EFN) basis, as is done for new engine certification, is an effective method for reducing the amount of testing needed for modified parts as there are about 168 engine families for these model years. These 2007-2009 engines were designed with DPFs as part of their configuration and therefore have systems to monitor and control DPF operation including regeneration, and proper engine function. As such, differences between the OEM DPF and aftermarket DPF may result in differences in engine performance, impacts to vehicle use, emissions non-compliance, device malfunction or damage, or engine damage.

Staff reviewed new engines certification documents, consulted with engine and aftertreatment manufacturers and other stakeholders, and conducted extensive literature

reviews. All of this information allowed staff to identify a reasonable approach to defining the ECG. After staff's investigation of 2007-2009 heavy duty diesel engines and emission control technologies staff suggested a method based the OEM part number and would decrease the testing cost from 168 EFNs to around 40 parts numbers. These OEM part numbers are publicly available. This became the basis for staff's initial proposal, presented at the second public workshop. In response, staff received numerous comments and suggestions from interested parties. Aftermarket DPF manufacturers stated that the testing costs would be so expensive as to be cost-prohibitive. Based upon these comments and recommendations, staff eliminated the OEM part number requirement and proposed a broader definition for the ECG, as described above. Staff considered comments received and assessed the OEM engines and aftertreatment configuration for these model years to identify 6 major emission control groups based on OEM engine manufacturer, OEM market share, and aftertreatment configuration. Staff's reduction of the number of ECGs would substantially reduce the testing cost while still acknowledging differences in engine design among the major OEMs that may affect engine and aftermarket part durability and functionality. This reduction in cost would encourage participation in the aftermarket DPF program.

However, OEM manufacturers responded with concern that the categories were too broad, that different engines needed to have completely different DPFs, not just different sizes of the same product. Staff considered all comments and concluded that the test procedure is robust enough to be able to handle the different engines within a given ECG, provided an appropriate "worst case" engine is selected by the applicant and approved by ARB. However, the differences between engines made by different manufacturers are too extreme for one DPF to handle, so staff could not make the ECG any broader. To cover all kinds of emission control technologies and specifications of 2007-2009 heavy duty diesel engines, an individual emission control group for a unique emission control technology for uncatalyzed DPF plus burner is added to the previously proposed 6 ECGs. Staff then made its final proposal of seven ECGs, with potentially reduced testing for a subcategory.

An additional consideration is that, in the marketplace, OEM DPF part numbers may be superseded by a different OEM replacement part number. For example, there may be different part numbers in the marketplace due to canning variations or different suppliers, which do not affect performance, that the OEM considers equivalent replacements. If the OEM considers all these DPF part numbers to be equivalent for the same engine, staff would consider them as all belonging to a single ECG.

2. Testing Requirements

The purpose of testing requirements in ARB's proposed Procedure is to ensure the modified part's compliance with emission standards, durability and compatibility with the engines. Staff believes all testing elements are essential to ensure a procedure robust enough to thoroughly evaluate the applicant's modified part. Because these modified parts are not part of the originally designed system, it is necessary to simulate real

world use, along with performing emission testing to ensure continued emission compliance.

a. Test Fuel and Lubricant Oil

Testing of fuel and lubricant oil is necessary to ensure that all applicants are using compliant fuel and oil. Non-compliant fuel could affect the emission test results and non-compliant oil could affect the lab aging process. This could potentially result in a favorable testing outcome for a device which may not be suitable for approval if used with appropriate oil and fuel.

Fuel testing requirements for emission testing (including degreening) and for lab aging and field service accumulation are slightly different. Emission testing requires the test fuel must meet California's diesel fuel specifications described in Sections 2280-2283, Title 13 of the California Code of Regulations (CCR). The fuel (or batch of fuel purchased) used must provide documentation of its compliance based on analysis using the American Society for Testing and Materials (ASTM) test methods specified in the Procedure. At a minimum, the fuel's content of sulfur, aromatics, polycyclic aromatic hydrocarbons, and nitrogen, and the cetane number must be measured and reported. ARB may ask for additional properties to be reported if evidence suggests those properties may affect functioning or emission compliance of the OEM or aftermarket DPF. The results of these analyses must be included with the manufacturer's final application.

Laboratory aging and field service accumulation requires the test fuel must meet either California's diesel specifications or U.S. EPA's diesel fuel standards set forth in Title 40, Code of Federal Regulations (CFR), Part 80, Subpart I². Allowing either state or federally compliant fuel for the aging and field service allows the applicant to use any commercially available, compliant fuel. The applicant shall provide the information that the test fuel meets the specifications for California or federal fuel for the lab aging and field service accumulation. The applicant may choose to perform the fuel analysis or to submit sufficient documentation of the test fuel content.

ARB's proposed Procedure requires the lubricant oil exposure testing during the DPF lab aging period. It is necessary to require the lubricant oil to meet OEM engine lubricant oil specifications and the same lubricant oil must be used throughout the laboratory aging for the modified part. The oil serves a specific purpose in the laboratory aging process, as described in Section C.2.d, below, so the simulated aging might be adversely affected by non-compliant oil.

² *Motor Vehicle Diesel Fuel; Nonroad, Locomotive, and Marine Diesel Fuel; and ECA Marine Fuel*, Title 40, CFR, Part 80, Subpart I, as it existed on February 12, 2016..

b. Testing Sequence

The Procedure specifies a standard protocol to test all modified parts for emissions compliance and durability. All applicants must follow the standardized testing protocol. This protocol is illustrated in Figure 1. This standardization allows for consistency and repeatability in testing. It prevents different testing for different systems/engines where it would be impossible to translate data, results, and information across systems, test programs, engines, and even applications. The applicant cannot propose its own testing, as allowing this would require significant staff time to compare the two methods to show the alternate method is as robust as the testing protocol proposed by staff.

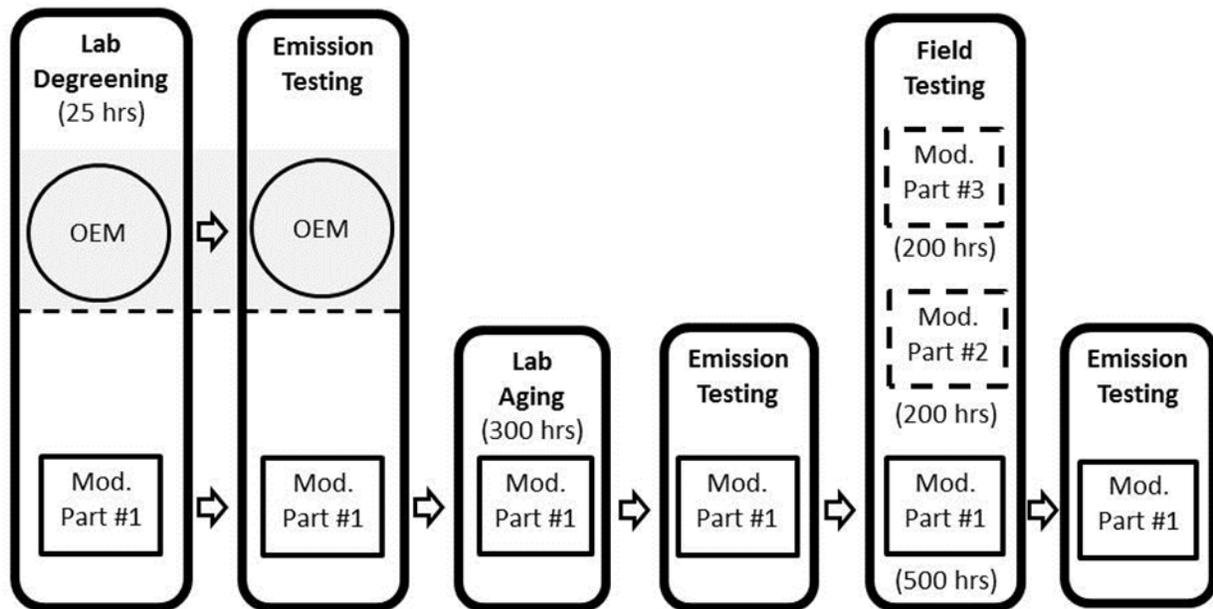


Figure 1: ARB proposed testing sequence for modified part

The testing sequence shall be as follows:

- Degreen a new OEM DPF and a new modified part.
- Conduct DPF catalytic activities check through either nitrogen dioxide (NO₂) emission test or soot accumulation test.
- Conduct emission testing including regeneration emission testing for both the degreened OEM DPF and the degreened modified part.
- Perform laboratory aging (engine dynamometer) on a new (or degreened), modified part for a minimum of 300 hours.
- Conduct emission testing of the laboratory-aged modified part.
- Remove the laboratory-aged modified part from the lab and install it on an appropriate vehicle for a field service accumulation period for a minimum of 500 hours.
- Remove the field-aged modified part and conduct emission testing.

- Conduct two additional field demonstrations, for a minimum 200 hours each, on different engines and applications from within the same ECG. These modified parts do not require emission testing.

It is particularly important to perform the field service accumulation on the modified part after this DPF has been laboratory aged. This ensures that the modified part tested in the field has been in use for some time. An aged modified part is more likely to exhibit a problem in field testing, compared to a brand new modified part, and helps assess how the modified part will perform in actual use over an extended period of time. Field testing alone is insufficient to evaluate a modified part, as field testing conditions can be highly variable and would only prove that the modified part is durable and compatible for the particular application chosen.

c. Laboratory Degreening Protocol

Applicant must degreen the OEM DPF and the modified part using either Federal Test Procedure (FTP) heavy-duty transient cycle or 13 modes Supplemental Emissions Test (SET) for a total of 25 hours. The DPFs are degreened prior to emission testing. Performing emissions tests on brand new DPFs that had not been degreened would not be an appropriate evaluation of their emission reduction effectiveness because some devices require a “break in” or aging period to stabilize in function.

The applicant must use the emission test engine for this degreening process. It is the most cost-effective way to use the emission testing engine because 1) this engine will be compatible with OEM DPF and modified part; 2) the emission testing of the OEM DPF would be considered as engine validation and this would save some testing costs. In addition, the test engine must be in a proper state of maintenance, not displaying any illuminated Malfunction Indicator Lamp (MIL) or having any Engine Manufacturer Diagnostic (EMD) fault code, and meeting its original certified emissions. This requirement will ensure valid emission testing.

This degreening period of 25 hours should include at least 1 regeneration event. Backpressure, exhaust temperature (DPF inlet and DPF bed), and other parameters (revolutions per minute (RPM), torque and any ECU codes if applicable) must be recorded for each test run. These data are necessary to evaluate the performance of the DPFs, particularly during the regeneration event(s).

d. Laboratory Aging Protocol

To demonstrate the durability and continued emission control effectiveness of the aftermarket DPF, staff developed an accelerated, laboratory aging protocol to age the new modified part under controlled laboratory conditions. It is a more cost effective method for evaluating durability and deterioration than a prolonged field testing.

Applicants must perform laboratory aging on the degreened modified part for a minimum of 300 hours. This accelerated aging process deteriorates the DPF in a

similar manner and to a similar degree as simply aging the unit in the field for approximately 273 hours of DPF regenerations, presuming the regeneration temperature is 650°C in the field. This duration of laboratory aging is equivalent to an average of 4,260 hours of engine/truck operation time in field, but conducted in a much shorter timeframe. The details for this lab accelerated aging calculation will be discussed in the next section. Subsequent emission testing on the aged modified part ensures that the part is still durable and compliant with all requirements in the Procedure, even after simulated extensive use in field.

Accelerated aging is used in the aftermarket catalytic converter procedure to prove that the part is both durable and meeting emission standards after the equivalent of at least 50,000 miles of use (the length of the warranty period). However, the aging method developed for catalytic converters on gasoline engines is not suitable for direct application to DPFs and diesel engines. Specifically, it does not sufficiently address physical and chemical methods of deterioration that are of greater concern for diesel engines and DPFs.

This required staff to develop a laboratory aging protocol that was both tailored to DPFs and diesel engines and suitable to be used as a general laboratory aging protocol in the proposed evaluation procedure. In developing an ARB-modified accelerated aging cycle, staff spent extensive time researching literature and consulting with individual stakeholders. A key aspect of this aging cycle is the incorporation of the effects (i.e., stress) from regular DPF regenerations. DPF regeneration is a high temperature, periodically occurring event that is a necessary part of normal filter functions in order to remove the accumulated soot. This high temperature event means that the filter is regularly (e.g., every 8-16 hours) exposed to changes in temperature. For example, the catalyzed DPF in an active regeneration system (e.g., fuel injected to reach required regeneration temperature) may experience a temperature change from 250°C up to 600°C and back down to 250°C in 13 minutes³.

The aging protocol also considers the effects of other important variables such as lubricant oil exposure (lubricant oil exposure is a major source of catalyst poisoning and deterioration); temperature variations within the DPF itself, and the effective aging time based on actual and desired aging temperatures.

High temperature and lubricant oil exposure are major sources of DPF catalyst deterioration. This proposed Procedure develops a laboratory accelerated aging protocol to simulate not only the high temperature exposure but also the lubricant oil exposure. The ARB proposed laboratory accelerated aging protocol targets oil consumption rates of the test engine over 100,000 miles using observed on-road heavy-duty diesel engine field average oil consumption (0.06% of fuel rate)⁴ for a 300-hour

³ Johnson Matthey, 2015. *Emission Control Technologies – Active DPF Regeneration*. <http://ect.jmcatalysts.com/Active-diesel-particulate-filter-systems-DPF-johnson-matthey>. Last accessed April 10, 2015.

⁴ Khalek, I.A.; Blanks, M.G.; Merritt, P. *Phase 2 of the Advanced Collaborative Emissions Study*; Coordinating Research Council (CRC) Report ACES-Phase 2; CRC: Alpharetta, GA, November 2013;

laboratory accelerated aging period. This 100,000 miles represents the engine/truck operation in the field. Furthermore, the Procedure also provides methods to track actual oil consumption during the aging period.

The requirement of multi-point temperature measurement in the proposed accelerated aging protocol is intended to address the temperature variations within the DPF. DPFs are wall-flow devices, and there are many factors including DPF core material, catalyst coating and soot loading which affect the heating rate and temperature distribution inside of the DPF. In order to better monitor the temperature variations inside the DPF, staff proposed a multi-point temperature measurement method. This method will use 13 temperature sensors (0.032" K-type thermocouples) to measure multi-point temperatures. This multi-point temperature measurement will provide a better and cost-effective evaluation of DPF temperature, especially for the DPF regeneration temperature.

Staff incorporated manufacturer suggestions to allow use of a surrogate or "mule" engine for aging purposes and to use a steady-state instead of transient cycle for the aging process. Accelerated aging stresses the DPF as well as the aging engine. It would not be cost effective or practical to require that the 2007-2009 emission test engine be the same as the aging engine. However, the mule engine must still be able to meet all target times and temperatures of the aging protocol. Transient cycles are typically used for emission testing to emulate real-world driving behavior but provide no benefit over steady-state cycles for accelerated aging purposes.

This lab aging protocol is necessary to ensure the part is durable and will reduce PM and emissions from the engine. A DPF that is not durable enough would need replacement sooner, costing the end user more money if the device were out of warranty. A vehicle with a broken DPF will emit uncontrolled PM emissions. In addition, the aging time is necessary to evaluate any safety issues that might arise during prolonged use. Under certain conditions, a malfunctioning DPF can cause runaway regenerations or catastrophic failures that could damage the engine and/or vehicle or be a hazard to the operator.

e. Laboratory Accelerated Aging Calculations and Considerations

This section explains the methodology used by ARB staff in developing the ARB Modified Aging Cycle to be used for the 300 hours of laboratory accelerated aging in the proposed Procedure.

ARB's proposed laboratory aging protocol addresses three aspects of DPF durability and deterioration: DPF (core material) stability and durability under frequent rapid

http://crao.org/reports/recentstudies2013/ACES%20Ph2/03-17124_CRC%20ACES%20Phase2-%20FINAL%20Report_Khalek-R6-SwRI.pdf. Last accessed December 24, 2015.

temperature change conditions; DPF (both core material and catalyst) durability and deterioration under high temperature exposure conditions; and DPF (both core material and catalyst) durability and deterioration by ash loading (through accelerated lubricant oil exposure).

Staff reviewed data gathered during Phase 1 of the Advanced Collaborative Emissions Study (ACES)⁵ in order to estimate the amount of time (in hours) spent during regeneration. Four 2007 heavy-duty diesel engines were tested in this study. Table 9 in the final report (cited and shown here in this document) describes the number of active regenerations per test. The DPFs were regenerated every 8 to 16 hours and each regeneration event lasted 30 minutes (0.5 hour) to 90 minutes (1.5 hours). Staff calculated the average values for the data listed in Table 9. Engines were regenerated every 14 hours and each regeneration event lasted 56 minutes (0.94 hour).

TABLE 9. NUMBER OF ACTIVE REGENERATIONS PER TEST

Test Cycle	Number of Cycles	Number of Regenerations per Cycle			
		Engine A	Engine B	Engine C	Engine D
FTP-w	3	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0
FTP-wo	3	1 ^c , 1 ^c , 1 ^c	0, 0, 0	0, 0, 0	0, 0, 0
CARBx-ICT	2	0, 0	0, 0	DPF Crack	0, 0
CARBz-CH	2	0, 1 ^c	0, 0, 0	DPF Crack	0, 0
16-Hour	3	1, 1, 1	2, 2, 3	1, 1, 1	1, 1, 1
Approximate Time of an Active Regeneration State, minutes (16-Hour Cycle Only)		75 ^a	90 ^a	30 ^a	30 ^b
^a During this time, active regeneration via exhaust fuel injection or via an exhaust burner may or may not be on all the time. E.g. During the 75 minutes with Engine A, exhaust fuel injection may shut off at low exhaust temperature and may come back on at high temperature. ^b For Engine D, this is the actual time of the active regeneration ^c Dosing occurred during a portion of each FTP, but under the same active regeneration state.					

ARB's laboratory aging protocol lasts 300 hours with 150 active regenerations (1 aging cycle lasts for 2 hours and one third of the time is spent in active regeneration). 150 active regenerations simulate 150 x 8 = 1200 to 150 x 16 = 2400 hours engine/truck operation in the field.

Furthermore, accelerated aging is an artificial situation intentionally subjecting a DPF (including core material and catalyst) to conditions that incorporate higher temperature and lubricant oil consumption than in the field. The required target temperature for the aging cycle active regeneration is 700°C, which is higher than the average active regeneration temperature experienced in the field. Active regeneration DPF bed

⁵ Khalek, I.A.; Bougher, T.; Merritt, P. *Phase 1 of the Advanced Collaborative Emissions Study*; Coordinating Research Council (CRC) Report ACES-Phase 1; CRC: Alpharetta, GA, June 2009; <http://www.crao.org/reports/recentstudies2009/ACES%20Phase%201/ACES%20Phase1%20Final%20Report%2015JUN2009.pdf>. Last accessed December 24, 2015.

temperatures in the field range from 550-650°C⁶. The Arrhenius equation can be used to relate time and temperature⁷:

$$\frac{t_2}{t_1} = \exp \left[-\frac{E_a}{R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \right]$$

Where

R is the universal gas constant (8.315 Jmol⁻¹K⁻¹)

E_a is the activation energy; 150 kJmol⁻¹ is used for a traditional PGM catalyst.

T₂ = target temperature of 700°C (973 K).

T₁ = Active regeneration temperature in the field of 650°C (923 K).

t₂ = 100 hours; the equivalent aging time at 700°C (973 K).

t₁ = equivalent aging time at 650°C (923 K).

The calculated value for t₁ is then 273 hours of equivalent time in field for the DPF. This is an approximation since the target temperature of 700°C is allowed to vary by ±50°C during the testing.

Based on average regeneration frequency (14 hours) and duration (0.94 hour) from the ACES study, the number of regeneration events during this time would be 273/0.94 = 290 times. The total engine/truck operation time in the field would then be 290 x 14 = 4,060 hours. The ARB proposed lab aging protocol also includes 200 hours normal engine operation time. The lab aging protocol simulates a total of 4,260 hours (or 191,700 miles with a truck running at 45 mph) actual engine/truck operation in the field.

In summary, the ARB proposed lab aging protocol simulates average 4,260 hours (or 191,700 miles) of engine/truck operation in the field.

f. Field Service Accumulation

The applicant must demonstrate, to the satisfaction of the ARB, the durability and compatibility of the modified part in the field. The durability demonstration consists of the modified part aged in a laboratory (through 300 hours accelerated aging) and then deployed in the field (through 500 hours field service accumulation) combined with emissions testing at the end of the each demonstration period.

The 500 hours of field service accumulation is the last stage of the testing. The laboratory-aged, modified part must be installed on a representative engine and vehicle and operated in the field for a minimum of 500 hours. This time in field is essential to

⁶ Majewski, W. A. Ecopoint, Inc. 2005. *Diesel Filter Regeneration*.

https://www.dieselnet.com/tech/dpf_regen.php. Last accessed November 19, 2014.

⁷ EPA, 2013. *Heavy-Duty Highway Compression-Ignition Engines and Urban Buses -- Exhaust Emission Standards*. U.S. Environmental Protection Agency, March 6, 2013.

test that the aged DPF functions well as an integrated part of the entire system in a real-world application (e.g., does not cause engine damage, show inappropriate regeneration behavior, trigger fault or error codes, or experience loss of physical integrity). While this field testing is primarily for evaluating compatibility, the 500 hours do contribute minor additional time for testing modified part durability. Testing results and data must be submitted to ARB. The applicant must also provide a written statement from an ARB-approved third party, such as the owner or operator of the vehicle or equipment used. The statement must describe overall performance, maintenance required, problems encountered, the results of a visual inspection, and any other relevant comments.

g. Additional Field Demonstrations

Additional field demonstrations of the modified part are important to further establish compatibility of the modified part with other engines within the ECG. At least two additional, 200-hour field demonstrations are required on engines from the same, proposed ECG, but these engines must be different from the one used for the 500-hour field service accumulation. Similar requirements are needed for the field testing as the primary 500-hour field demonstration described above. Testing results and data must be submitted along with a written statement from a third party (e.g., owner or operator of vehicle used) describing the overall performance of the modified part and any problems encountered. These modified parts are not required to be emission tested afterward, as the primary reason for these tests is to establish compatibility on more than one engine within the ECG. These additional field demonstrations are essential to show that the applicant's modified part is compatible with multiple engines within the ECG. Incompatible DPFs can cause decreased PM control and/or runaway regenerations that can cause engine damage and/or present safety hazards.

h. Emission Testing

The primary goal of emission testing is to ensure that modified parts comply with emission standards and do not produce harmful secondary emissions. VC 27156 specifies that a part may be exempted from anti-tampering provisions only if it will not reduce the effectiveness of any required pollution control device nor cause vehicle emissions to exceed applicable standards. Therefore, the applicant is required prove its device's effectiveness and ability to comply with emission standards.

In general, the proposed Procedure establishes emission testing requirements to support the modified part application. The Procedure specifies the same fuels and testing cycles (FTP heavy-duty transient cycle and SET) used by OEM manufacturers to certify new engines. It also specifies the number of tests to be run for each testing stage. Additionally, backpressure, exhaust temperature and other parameters must be recorded for each test run. There is also a catalytic activity test comparison, which is comprised of either NO₂ measurement or a soot accumulation test. Another important aspect of emission testing is to include emissions during regeneration events. The modified part is also evaluated for the potential to form secondary emissions.

There are three stages of emission testing, which were discussed in the section “Test Sequence.” Emission testing is performed of the OEM DPF and modified part in order to compare results and ensure that the modified part is not behaving too differently from the OEM DPF nor causing the engine to deviate from its normal behavior. Emission testing is performed on the modified part after the laboratory aging and after the field aging to prove the emission compliance and engine compatibility for these two durability demonstrations. Details of this ARB proposed accelerated aging protocol is discussed, above.

After successfully completing 300 hours of laboratory aging, the modified part will be tested for emission compliance and engine compatibility. Then this modified part will be deployed to a field truck to complete the 500 hours of field testing. Although this 500 hours of field testing is relatively short compared to the simulated laboratory aging period (300 hours of lab aging simulates 1,656-8,736 hours of field aging), the modified part has been aged in the field to simulate extensive use and engine compatibility. This last stage of testing is necessary to prove a part aged under robust controlled laboratory conditions is still durable and compatible with the ECG by requiring it to be deployed in an actual field demonstration. At the conclusion of the field trial, emission testing is again conducted to prove the emission compliance and engine compatibility for this field-aged modified part.

1. Emission Compliance

All emission results must meet certification emission standards as required by the VC and there must not be any fault codes or warnings during the emission testing. This applies to the initial testing of the OEM and modified part DPFs, as well as the testing of the lab-aged, modified part and the lab-aged, field-tested modified part.

2. Regenerations

Another important aspect of emission testing is the requirement to include emissions during regeneration events. 2007-2009 model year HHDEs equipped with DPFs capture and store diesel PM and periodically burn it off using some external energy input. The Procedure requires that emissions be measured during these regeneration events. DPF regeneration emission testing must be part of the approved test plan and should follow U.S. EPA guidance documents Cisd-06-17 (issued August 7, 2006)⁸ and Cisd-06-22 (issued November 6, 2006)⁹ and include factors relevant to the target emission control group including, but not limited to: test cycles; number of test cycles necessary to cover the entire DPF regeneration event; methods to pre-load the filter, trigger DPF regeneration; methods to measure and record exhaust temperature, exhaust backpressure, and engine speed; and methods to sample and record exhaust flow and criteria pollutants. The DPFs must be appropriately loaded with soot at the

⁸ U.S. EPA, 2006a. *Heavy-Duty Highway Guidance for Infrequent Regeneration of Diesel Particulate Filters*, Compliance and Innovative Strategies Division (CISD), Cisd-06-17, (August 7, 2006)

⁹ U.S. EPA, 2006b. *Alternative Heavy-Duty Highway Guidance for Infrequent Regeneration of Diesel Particulate Filters*, Cisd-06-22, (November 6, 2006)

time of the regeneration testing. The final emission testing results must include a calculation method for adjusting the emission level to account for frequent/infrequent regeneration adjustment factors as specified by Title 40, CFR, Part 86, Section 86.004-28(i)¹⁰. As these modified parts are not part of the original system, it is essential to evaluate their ability to function with the engine and ECU to properly regenerate.

3. Catalytic Activity

There is also a catalytic activity test comparison, which is comprised of either NO₂ measurement or a soot accumulation test. The purpose of this test is to show that, for catalyzed DPFs, passive regeneration is being properly performed, even after lengthy use, by assessing the soot oxidation rate. This is an essential aspect of a DPF's function, so it is necessary to require this test. The applicant may choose either NO₂ measurement or a soot accumulation test.

Passive regeneration relies on the oxidation of soot in the presence of NO₂, which can occur at much lower temperatures, as explained above. A catalyst is used to convert NO present in the exhaust to NO₂ which, in turn, oxidizes the unburned hydrocarbon PM (soot). Therefore, measurement of NO₂ provides an assessment of the DPF's catalytic activity. Emissions of NO₂ from the degreened modified part must be within 15% of the OEM, emissions from the lab-aged modified part following must be no more than 15% below the degreened modified part, and emissions from the field-aged modified part must be no more than 20% below the lab-aged modified part.

The soot accumulation test measures the soot oxidation rate more directly, by weighing the DPF before and after a 6-hour continuous FTP cycle, as well as at 2-hour intervals during the FTP. Both the OEM and the modified part DPFs are tested. The soot accumulation rate of each DPF is determined by linear regression and the results compared to each other. The accumulation rate of the degreened modified part shall not be greater than 20% below of the OEM DPF rate.

4. Comparison of Modified Part to OEM

The proposed testing requires comparisons between OEM and modified part performance. These comparisons are needed to evaluate the ability of the modified part to function as a substitute for the OEM DPF. The ECU is programmed to expect certain behaviors from the OEM DPF. These assumptions factor into how the OEM DPF ECU controls regeneration (initiation, duration, termination). For example, if the modified part burns off soot at a slower rate compared to the OEM DPF during the engine operation, the accumulated soot may trigger the regeneration early. This discrepancy will lead to more frequent regenerations and increase the risks of DPF failure and potential emissions. The proposed Procedure considers this discrepancy

¹⁰ *Compliance with Emission Standards*, CFR, Title 40, Part 86, Subpart A, §86.004-28(i), as it existed on February 13, 2016

between OEM DPF and modified part, and includes testing requirements (i.e. soot accumulation testing for the DPF catalytic check) and approval criteria. In another example, if the modified part burns off soot at a slower rate compared to the OEM DPF during regeneration, then the ECU may mistakenly determine the filter has completely regenerated (i.e., has been cleaned) and end the regeneration when in fact the modified part still has remaining soot. The ECU may mistake this remaining soot for inert ash and not trigger any corrective actions to properly clean the filter of soot. Over time this remaining soot can build up and, if not removed, can lead to more frequent regenerations, an uncontrolled regeneration, filter plugging, or other problems. Therefore, it is important that the modified part be compared to the OEM DPF during testing to show they act similarly and to perform this comparison after the OEM and modified part DPF undergo the exact same degreening process.

Staff is proposing passing criteria for these three stages emission testing. The passing criteria are determined due to several factors. First, any emission testing results must comply with emission standards which are required for all aftermarket regulations. Second, since this is a modified part and not an exact replacement for the OEM DPF, staff is not expecting the modified part to behave exactly like it in every respect. However, if the modified part deviates significantly from the OEM, it not only might exceed emission standards, it could cause issues with proper DPF regeneration and negatively impact engine behavior and operation. Third, some criteria are based on the test-to test variability, the instrumentation capability and measurement accuracy.

For the first stage of emission testing (comparison of degreened OEM and modified part DPFs), the average backpressure and exhaust temperatures are required to be within 10 percent of OEM values and emissions of CO, NMHC, NO_x (or NO_x plus NMHC), and PM from the degreened modified part must not exceed the applicable new engine certification standards. Significant differences in performance would indicate that the modified part is neither suitable for nor compatible with the engine. The 10 percent was determined to be a reasonable metric based upon previous experience with verification (*Verification Procedure, Warranty and In-Use Compliance Requirements for In-Use Strategies to Control Emissions from Diesel Engines*. CCR, Title 13, Sections 2700-2711) and good engineering judgment. For example, reasonable NO_x and PM values will ensure the valid and correct engine calibration, and comparable exhaust temperature and backpressure will ensure reasonable engine operation conditions including regeneration frequency.

For the second and third stage, emission testing is also conducted at the conclusion of the laboratory aging period and field service accumulation period. Then the results of the subsequent modified part emission testing are compared to the previous results to ensure the modified part still complies with all emission requirements. Again, emissions must meet the certification standards. Average exhaust temperatures shall be within 10 percent of the average value from the previous emission test and average backpressure shall be within 20 percent.

5. Secondary Emissions

The modified part must also not result in potentially harmful secondary emissions and must not pose a safety risk. This requirement is necessary to protect the public health. The proposed Procedure requires ARB to investigate any potential for secondary emissions of concern from the modified part. Some forms of catalysis used in DPFs or some fuel borne catalysts used with DPFs have already been shown to significantly increase the toxic components of their emission. Therefore, ARB staff deems it essential that additional analyses be required in these cases. The following criteria form the basis for ARB's determination if any additional analyses are required:

- The nature of any substance added to the fuel, intake air, or exhaust stream,
- Whether a catalytic reaction is known or reasonably suspected to increase toxic air contaminants or ozone precursors,
- Results from scientific literature,
- Field experience,
- Any additional data or information, and
- Good engineering judgment.

Additional analyses may include, but are not limited to, measurement of benzene, 1,3-butadiene, formaldehyde, acetaldehyde, polycyclic aromatic hydrocarbons (PAH), nitro-PAHs, dioxins, and furans. Staff proposed the most updated test methods for such analysis.

i. Maintenance

Only scheduled maintenance on the engine and modified part may be performed during the laboratory aging, field service accumulation and field demonstrations. The applicant may perform necessary maintenance (i.e. ash removal) after the 300-hour laboratory aging and prior the second stage emission testing. A description of the maintenance, including the timestamp (miles, years, or hours) must be included with the results of the testing. Additional maintenance or repairs might impact the results of the testing.

j. Other Requirements

Noise Level Control: Any diesel emission control system that replaces a muffler must continue to provide, at a minimum, the same level of exhaust noise attenuation as the muffler with which the vehicle was originally equipped by its manufacturer. This requirement is necessary to avoid an adverse impact on the vehicle and/or operator.

Other Informational Requirements: The applicant must describe fuel and oil requirements, maintenance requirements, and provide an owner's manual and any additional information that ARB may require to assess environmental impacts associated with use of the diesel emission control strategy. This information is necessary for ARB staff to perform a detailed evaluation of the applicant's modified part DPF.

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