Regulatory Support Document

An Updated Assessment of the Feasibility of Trap-Oxidizers

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I. Introduction

On March 5, 1980, EPA published a Final Rule which, for the first time, established particulate emission standards for diesel-powered light-duty vehicles and light-duty trucks (45 FR 14496). That rulemaking established standards of 0.6 g/mi for all 1982 through 1984 diesel passenger cars and light trucks. The 1985 and later model year standards were set at 0.2 g/mi for passenger cars and 0.26 g/mi for light-duty trucks. These latter standards were clearly "technology-forcing," (i.e., EPA could not show at the time of promulgation that the standards were feasible but projected that the standards could be met by 1985). The Agency's technical projection was based on the expectation that trap-oxidizers would be reasonably perfected by the 1985 model year.

The feasibility of trap-oxidizers has been a controversial issue. Since compliance by the entire fleet with the 1985 standards is dependent upon the successful application of trap-oxidizers, the Agency has constantly monitored the progress of trap-oxidizer development. EPA published a Request for Information on June 17, 1981 which announced that the Agency would be preparing a study of the status of trap-oxidizer development (45 FR 31677). In March 1982, EPA published the "Trap-Oxidizer Feasibility Study" (hereafter referred to as the Feasibility Study) which was based on the Agency's own work with trap-oxidizers as well as written comments from interested parties. Comments generally included information available as of the end of 1981. This study formed the basis of EPA's Notice of Proposed Rulemaking (NPRM) on December 1, 1982 which proposed to delay implementation of the 1985 particulate standards for two years (47 FR 54250).

Many comments on the current status of trap-oxidizer development were received February 17, 1983, which was the closing date for comments on the NPRM.* These comments generally included information on manufacturer development programs through the end of 1982. In addition, a study entitled "Trap-Oxidizer Technology for Light-Duty Diesel Vehicles: Feasibility, Costs, and Present Status," (hereafter

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* A few vehicle manufacturers claimed that part or all of their technical comments to this rulemaking contained proprietary information and requested that EPA treat such sections as confidential material. The Agency has reviewed the comments claimed to be confidential, and as a general rule the information presented therein is representative of material already in the public domain as well as of comments to this rulemaking which were not claimed to be confidential.

referred to as the Technology Study) which was completed on March 20, 1983 under contract to EPA, involves a recent independent analysis of trap-oxidizer status.* These sources of information make it possible for EPA to assess the state of trap-oxidizer development as of the end of 1982, a full year later than the assessment possible in the Feasibility Study. This study is the Agency's summary of the current status of trap-oxidizers and its projections of future developments. As such, this study serves as the technical support document for EPA's decision to delay the particulate standards for two years.

II. Highlights of the Feasibility Study

A. Status of Development

The Feasibility Study found that research into trap-oxidizers had advanced significantly since the 1985 particulate standards were promulgated. Manufacturers had identified two basic trap-oxidizer designs and were concentrating their research efforts on perfecting these devices. One design utilized a porous, ceramic honeycomb monolith (hereafter the ceramic monolith trap) similar to the ceramic substrate used in catalytic converters on many gasoline-fueled vehicles. The other design utilized an alumina-coated wire mesh (hereafter the wire mesh trap). This filtering medium was often coated with a catalytic material. The presence of a catalyst can aid regeneration by lowering the pre-trap exhaust temperature which is necessary to initiate the particulate burning process. The catalyst functions to "light-off" or initiate oxidation of the hydrocarbon (HC) portion of the trapped particulate or HC and carbon monoxide (CO) in the exhaust, thereby generating additional heat and higher temperatures within the trap-oxidizer. The importance of this will become clearer later in this section.

The Feasibility Study found that these trap designs were very satisfactory. Trapping efficiency and backpressure were judged to be acceptable for both new traps and traps with up to 50,000 miles of use that had been regenerated 50-100 times. Although many cases of trap failure had been reported, durability problems were almost always due to excessively high temperatures inside the trap during regeneration. As stated above, traps had been tested up to 50,000 miles without problems when regeneration was properly controlled. Therefore, while trap materials and designs appeared to be satisfactory, the key to durability was properly controlling regeneration.

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* This study was prepared under EPA Contract No. 68-01-6543 by Energy and Resource Consultants, Inc., and is available for inspection in EPA Docket No. A-82-32.

The first step in properly controlling this process is an understanding of the conditions which are necessary to initiate and maintain regeneration. In these areas, the Feasibiltiy Study found that manufacturers had made significant progress in identifying the relevant parameters. For non-catalyzed traps, temperatures in the range of 500°-650°C and oxygen levels of 3-4 percent are required for 2-10 minutes (low temperatures being associated with the longer times and vice versa). The presence of a catalyst in the trap may be able to reduce the requisite temperature to as low as 310°-350°C.

Because the temperatures required for regeneration do not always occur during normal vehicle operation, manufacturers were developing several different systems to initiate and maintain regeneration. To provide the higher requisite temperatures associated with non-catalyzed traps, auxiliary fuel burners or electrical heating appeared to be quite workable, but would be relatively expensive and, in the latter case, would require extensive vehicle modifications. For catalyzed traps, simpler and less expensive systems could potentially be used because the extent to which the trap temperature must be raised is significantly less. Two regeneration systems being developed for this application were intake air throttling and exhaust stroke fuel injection.

The principal task that remained to complete the development of a completely functional trap-oxidizer was to integrate the trap designs and regeneration devices, identified above, into an automated system. Because of the complexities involved in determining trap loading, initiating particulate combustion under the proper oxygen and temperature conditions, and maintaining combustion without overheating the trap materials, some form of electronic control seemed necessary. These controls would be somewhat similar to those used on most gasoline-fueled automobiles. Automating the regeneration process was considered to be technically feasible given more development time.

B. <u>Leadtime</u>

The Feasibility Study divided the remaining development work on these systems into two basic categories: prototype and production. Prototype development culminates in a working model of the complete trap-oxidizer package, including a fully automated system for regeneration of the trap under a range of vehicle operating conditions. As discussed above, nearly all of the critical parts and design parameters of the system were either known or readily available. The remaining task in this area was to integrate the trap designs and regeneration devices into an automated package. Based on the technical difficulty of the remaining work, the Feasibility Study estimated that prototype development should be completed by about January 1983, but noted the inherent uncertainties in such projections.

Production development follows the completion of prototype development. This final phase of development includes assurance testing to refine the system further under a variety of real-life conditions, modifying the vehicle or engines to accept the trap system, acquiring production facilities and tooling, and completing emission certification testing. Development of leadtime estimates for these activities is subject to much less uncertainty than that for prototype development because no technological advances must be made.

The Feasibility Study found that many of the production-oriented activities could be accomplished concurrently. The critical path elements were identified as assurance testing and the acquisition of production facilities and tooling.

Two phases of assurance testing were believed necessary. Each phase would involve 50,000 miles of driving and last 3.5-5 months. Between these driving tests would be a 3-4 month period of data analysis. However, only the first driving phase and subsequent data analysis (7-9 months) were considered critical path elements, because manufacturers could begin to make initial production commitments after these tasks were complete.

The leadtime necessary for production facilities and tooling was estimated to be 18-24 months. This estimate was corroborated by projections that were previously acquired from heavy-duty engine manufacturers regarding production tooling and leadtime for a similar technology (i.e., catalysts for gasoline-fueled vehicles).

The total production development leadtime, then, consisted of 25-33 months from the completion of prototype development, which was projected to occur about January 1983. This schedule would result in trap-oxidizers being ready to be placed on production vehicles sometime between February 1985 and October 1985. Since vehicle production for a given model year historically begins around August of the previous calendar year, this led to two important conclusions. First, a delay of the new particulate standards beyond the scheduled 1985 model year was obviously necessary. Second, it was possible traps would be available for the 1986 model year (development completed before August 1985), but is was also possible that they would not be available on a nationwide basis until the 1987 model year (development completed after August 1985). The serious consequences of selecting an infeasible date led EPA to follow a conservative approach and, therefore, propose a delay of the particulate standards until the 1987 model year.

III. Reconsideration of the Conclusions of the Feasibility Study

A. Efficiency, Backpressure, and Durability Performance

The ceramic monolith honeycomb substrate appears to be the leading trap-oxidizer filter design. Every major light-duty diesel manufacturer marketing in the U.S. has conducted extensive test development programs with ceramic monoliths, supplied by either Corning Glass Works or NGK Insulators, Ltd., and the majority of recent test data supplied to EPA involved ceramic monolith traps. Recent submissions lend strong support to the conclusions of the Feasibility Study regarding efficiency, backpressure, and durability characteristics of ceramic monolith traps.

The results of two durability programs demonstrate the basic integrity of ceramic monolith trap designs under controlled regenerations. Daimler-Benz has just recently reported on a major trap-oxidizer development program performed in Denver in 1981.[1]* Daimler-Benz outfitted twelve of its Mercedes-Benz vehicles, six naturally aspirated and six turbocharged, with ceramic monolith traps of varying porosities and wall thicknesses. All of the naturally aspirated vehicles successfully completed 50,000 miles of testing with particulate levels generally around 0.05 g/mi. Daimler-Benz did not provide the collection efficiencies of the traps, but based on expected non-trap levels EPA estimates the efficiencies to have been on the order of 80 percent. None of the turbocharged vehicles completed 50,000 miles, apparently due to difficulties in regenerating the trapped particulate. The three traps with the lower wall thickness failed, while testing of the three vehicles with the higher wall thickness was halted at between 35,000 and 40,000 miles because of driveability problems. Although Daimler-Benz did report difficulties with driveability, and trap failures occurred on the turbocharged vehicles with the lower wall thickness, this program did indicate the ability of ceramic monolith traps to survive the vehicle environment for 50,000 miles if regeneration occurred properly. These results are particularly impressive in view of the fact that Daimler-Benz did not control regeneration conditions nearly as well as they would be under most regeneration systems, since no positive regeneration technique was used at all.

A second major ceramic monolith trap durability program was sponsored by the Agency in late 1981 and early 1982. The

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* Numbers in brackets indicate references which are listed at the end of the report.

Southwest Research Institute installed a ceramic monolith trap onto a 1980 Mercedes-Benz turbocharged diesel vehicle. Mileage accumulation was performed on the road, while regenerations were conducted under laboratory conditions. Emission tests were performed every 5,000 miles, with and without the trap. Particulate reduction was very near 90 percent for the entire 50,000-mile durability run. Backpressure levels were only moderately higher with the trap, and driveability was acceptable. (Very high backpressure adversely affects fuel economy and engine performance.) A more complete description of the test program and results is given elsewhere.[2] In general, the trap exhibited stability and high efficiency over the entire test. No unscheduled maintenance was performed on either the engine or the trap-oxidizer at any time after the testing began.

The catalyzed alumina-coated wire mesh trap design has also been extensively evaluated by nearly every major light-duty diesel manufacturer marketing in the U.S. Johnson Matthey, Inc. has been the primary supplier of catalyzed wire mesh traps. Johnson Matthey proved the basic durability of its trap design with a successful 50,000-mile demonstration on a 1981 Volkswagen Rabbit at Southwest Research Institute which was completed in January 1982. The results of the program were summarized in the Feasibility Study. Particulate reductions varied between 40 and 60 percent, though the trap was only designed to be 50 percent efficient due to the relatively low engine-out emissions of the Rabbit. The trap was also effective in reducing HC and CO emissions, which would be expected with a catalyzed trap. Only moderate backpressure levels were measured. This testing proved the general durability of the wire mesh filter and catalytic coating under proper regeneration conditions. In fact, due to the somewhat crude regeneration system used in this program, regeneration conditions (e.g., temperature, oxygen level) probably varied much more than they would under a more advanced regeneration system.

Few additional results were submitted to EPA on the catalyzed wire mesh design as a part of this rulemaking. Several manufacturers still have active programs involving wire mesh trap designs but did not submit new data on efficiency, backpressure, or durability. Other manufacturers seem to be concentrating their development efforts on ceramic monolith traps. However, EPA, in cooperation with Johnson Matthey, has recently undertaken a test program to investigate the possibility of a high-efficiency wire mesh design. The program is not yet complete, but preliminary results indicate that the wire mesh trap is capable of particulate reductions as high as 70 to 80 percent over the Federal Test Procedure (urban driving schedule) and 40 to 70 percent over the Highway Fuel Economy Test.[3] HC and CO emissions have been reduced by 80 percent over the Federal Test Procedure and by more than 90 percent over the Highway Fuel Economy Test. Based on these results, it appears that the catalyzed wire mesh design can provide relatively high collection efficiencies if so designed.

In conclusion, the Agency's analysis of recent information submitted to EPA and that which has been published in the open literature supports and strengthens the conclusions in the Feasibility Study concerning basic filter design and performance. In particular, the ceramic monolith trap is capable of maintaining particulate collection efficiencies of 70 to 90 percent with moderate increases in backpressure for up to 50,000 miles when regeneration conditions are properly controlled. Also, the catalyzed wire mesh trap can provide particulate reductions of 50 to 80 percent, along with significant HC and CO emission reductions, for 50,000 miles under controlled regeneration. The Agency is not aware of any attempt to accumulate more than 50,000 miles with either a ceramic monolith or wire mesh trap, but evidence suggests that successful operation beyond 50,000 miles is very probable if proper regeneration conditions are maintained.

B. Regeneration Mechanisms

Much of the industry's research in the last year has focused on regeneration. The following discussion will summarize the progress and status of trap-oxidizer regeneration development.

There are two general approaches to regeneration. Because of the variable nature of passenger car operation and the necessity of reliable and periodic regeneration, until recently most research in this area had concentrated on positive regeneration systems (those which actively increase exhaust temperature or otherwise promote regeneration). Positive regeneration systems involve a decision to regenerate the trap at a specific point in time with some special mechanism activated to ensure that regeneration occurs. A second approach, self-regeneration, relies on attaining regeneration conditions during normal vehicle operation without the activation of any special mechanism.

Several positive regeneration systems have been suggested. All of them share the basic function of raising the temperature of the particulate in the trap-oxidizer. For non-catalyzed traps, this typically involves either the addition of an auxiliary heat source or else the modification of engine parameters to raise exhaust gas temperature directly. Examples are fuel burners, electrical heaters, or air intake throttling. For catalyzed traps, positive regeneration systems can also include mechanisms which raise the HC and CO levels in the exhaust. The HC and CO are oxidized by the catalyst with the additional heat utilized to ignite the particulate. Proposed systems for raising the HC and CO levels for catalyzed trap systems include exhaust stroke fuel injection, temporary modification of engine parameters, and individual cylinder throttling. All of these possible regeneration systems have been described and analyzed in either the Feasibility Study, the Technology Study, or both. Only the most advanced positive regeneration systems will be discussed: the fuel burner for non-catalyzed ceramic monolith traps and exhaust stroke fuel injection for catalyzed wire mesh traps.

The fuel burner provides the additional heat necessary for regeneration by igniting an air/fuel mixture immediately in front of the trap inlet. The burner requires a fuel supply and fuel injector, a glow plug or spark plug to initiate ignition, and an oxygen supply. The oxygen may be supplied by a low-pressure air pump (air-fed burner) or by residual oxygen present in diesel exhaust (exhaust-fed burner). In addition, the burner can heat the entire exhaust gas flow (in-line burner), or can heat just the trap itself while the exhaust gas is routed away from the trap (bypass burner). All of these options have been investigated by various manufacturers.

Ford has published the most extensive results of testing of burner systems, both air-fed and exhaust-fed in-line systems.[4] Its most recent paper delineates Ford's extensive development and evaluation of an air-fed in-line burner.[5] Ford's burner utilized a burner flame stabilization housing containing a fuel atomizing nozzle, a spark plug, and combustion air provided by an external air pump. A short mixing cone was installed at the burner outlet to distribute the burner exhaust across the entire front face of the trap. The burner system was installed just upstream of the ceramic monolith trap, which was mounted at the outlet of the exhaust manifold. Ford found that a single burner fuel flow and air flow setting produced trap inlet temperatures adequate to initiate regeneration over a wide range of engine operating conditions (i.e., from idle to 50 miles per hour cruise conditions). Regeneration effectiveness, defined by Ford to be a measure of the ability to restore the trap to the zero-mile backpressure level, was more than 90 percent at trap inlet temperatures of 650°C with the burner functioning for two minutes.

Ford installed the trap/burner system onto a diesel vehicle and, after several attempts, succeeded in operating the system for a 1,000-mile durability test. During this test, 15 regenerations were successfully performed over a wide range of operating conditions. With accurate control of trap inlet temperature and flow rates, no damage to the trap was observed. Like all manufacturers, Ford also reported general problems with thermal shock cracking and melting of the ceramic monolith trap when regeneration was not properly controlled. However, it has found that limiting the maximum particulate loading and trap inlet temperature was effective in avoiding trap failure. Ford considers the primary remaining problems to be improving burner operation during transient engine operation and automating the burner control system. One simple solution to the transient operation problem is to go to a bypass burner system, which Ford is researching. The issue of controls will be discussed later in this section. Based on the results reported by Ford and other manufacturers, it is clear that manufacturers have made considerable progress during 1982 in defining satisfactory operation of burner regeneration systems.

The basic concept of exhaust stroke fuel injection is to create a diesel analogue of a misfire, by injecting additional fuel into one cylinder at the beginning of the exhaust stroke. This fuel is cracked into lighter HC and CO by the heat and pressure which still exist in the cylinder. The HC and CO are then exhausted on the piston upstroke and oxidized by the precious metal catalyst on the wire mesh trap. Johnson Matthey has stated that the exothermic reaction of the HC and CO produces a temperature rise of approximately 150°C to 200°C within the trap. The catalyzed wire mesh trap oxidizes particulate at approximately 350°C, so exhaust stroke fuel injection can initiate regeneration for catalyzed wire mesh traps at exhaust temperatures as low as 200°C. This system would not work for non-catalyzed traps.

Johnson Matthey utilized an early prototype version of exhaust stroke fuel injection on its 50,000-mile durability demonstration test completed in early 1982. When exhaust backpressure reached a certain level, the driver operated a manual lever which diverted fuel from one cylinder (which was in the compression stroke) to another (in the exhaust stroke), which initiated regeneration. Of the 46 regenerations attempted during the durability test, 37 were successful. The nine failures simply resulted in additional regenerations.[6]

The diversion of fuel from one cylinder to another results in the former cylinder being "starved," which can lead to loss of power and driveability. It will be necessary to modify the fuel injection system so that extra fuel can be provided to one cylinder without starving any other cylinder. This might be difficult for mechanical fuel injection pumps used on current diesel vehicles, but would likely involve fairly minor modifications (addition of solenoid valves) to electronically controlled injection pumps. Several reports have been published in the last year which indicate that microprocessor-controlled electronic fuel injection pumps are near production status, and it is known that a number of prototype diesel cars with such systems are currently being evaluated. The National Academy of Sciences has projected that electronically controlled pumps will become available by 1985.[7] The emergence of electronic injection pumps on production vehicles in this timeframe should ensure the feasibility of exhaust stroke fuel injection as a satisfactory regeneration technique for catalyzed wire mesh traps. The new pumps would also provide the opportunity for alternative means of providing HC and CO to the catalyzed trap, such as temporary modification of exhaust gas recirculation and/or injection timing.

Positive regeneration systems, such as the fuel burner for ceramic monolith traps and exhaust stroke fuel injection for catalyzed wire mesh traps, appear to be at advanced stages of development. They are the most understood regeneration systems and the most likely to be adopted for initial trap-oxidizer systems. Positive regeneration systems also tend to be relatively complex. Recently an important breakthrough in trap-oxidizer development has occurred with self-regeneration systems which would ensure particulate oxidation during normal engine operating conditions and thus be simpler than the positive regeneration systems. Self-regeneration was considered very unlikely at the time of the Feasibility Study. Most of this recent work has centered on the use of diesel fuel additives.

It is well known that catalysts can reduce the ignition temperature of carbon. Early research, however, had indicated that catalysts impregnated in the trap were ineffective in reducing the ignition temperature of particulate stored in the trap. More recently, it has been found that organometallic compounds added to diesel fuel can effectively lower the particulate ignition temperatures. When the fuel is burned, the metal is liberated from its carrier molecule and forms either a sulfate or an oxide which is distributed throughout the particulate in the trap-oxidizer. This is advantageous, because <u>all</u> the trapped particulate, not just the initial layer, is in contact with the catalyst.

The use of fuel additives is now the leading avenue of research for many manufacturers. Three manufacturers have published results from their additive programs: Ford, Volkswagen (VW), and General Motors.[8,9,10] These reports form the foundation for the following analysis.

Several organometallic fuel additives have been evaluated, including copper, lead, manganese, calcium, and various combinations of these. Table 1, from the Technology Study, summarizes the results of screening tests by Ford. Table 1 shows that all of the organometallic additives were effective in lowering the particulate ignition temperature. Copper was the most effective individual metal on a concentration basis, and the combination of copper and lead resulted in the greatest overall ignition temperature reduction. Volkswagen stated that

Table 1

Effects on Particulate Ignition
Temperature of Various Organometallic Additives

Additive	Ignition Temperature (°C)
None (baseline fuel)	426
0.5 g/gal calcium	268
0.5 g/gal lead	246
0.25 g/gal copper	232
1.0 g/gal lead	232
0.25 g/gal copper + 0.25 g/gal manganese	232
0.25 g/gal copper + 0.25 g/gal lead	224
0.25 g/gal copper + 0.5 g/gal lead	191

in order to be able to rely on self-regeneration, an additive must be able to induce regeneration at approximately 250°C. Table 1 indicates that all of the additive formulations were below 250°C except for calcium, which was just slightly above that level.

Manufacturers have reported promising vehicle tests with various fuel additives. Ford completed a 10,000-mile durability test with a ceramic monolith trap using an additive formulation of 0.25 gram per gallon (g/gal) copper (as copper naphthanate) and 0.50 g/gal lead (as tetraethyl lead) for the first 3,500 miles, and doubling the lead content for the remaining 6,500 miles. The mileage was accumulated with "normal" on-the-road driving. Ford reported that temperatures above 191°C were reached often during the testing, resulting in frequent regenerations. As a result, the oxidation process generally occurred with relatively low particulate mass loadings, which led to relatively lower peak trap temperatures as well. Ford stated that this would assist in avoiding trap thermal failure. The trap maintained a collection efficiency of more than 70 percent and exhaust backpressure seldom exceeded the clean trap backpressure by more than 50 percent, which also indicated that the trap was being regenerated frequently and effectively.

Volkswagen operated a diesel Rabbit with a ceramic monolith trap and a calcium additive of unknown concentration for more than 25,000 miles of "real world" mileage accumulation. At about 15,000 miles, particulate and fuel consumption levels rose, indicating that the trap was possibly filling with calcium deposits. In a second test, VW used a manganese additive with a Quantum turbocharged vehicle equipped with a ceramic monolith trap. The vehicle accumulated more than 12,500 miles on a chassis dynamometer at a constant speed of 31 miles per hour. This is probably close to a "worst case" scenario, as the power requirements and thus the exhaust temperatures are very low at such low-speed cruise conditions. Normal driving, even at low average speeds, typically includes frequent accelerations, which produce higher exhaust temperatures which would ease regeneration. That the trap successfully survived 12,500 miles of worst case operation indicates that additives should be able to induce self-regeneration under almost any possible usage pattern. VW also reported successful regeneration using additives in cold room testing at -20°C.

Although General Motors has an extensive program underway to evaluate fuel additives, it has not released many results. It is known that General Motors has one trap-equipped test vehicle which has accumulated nearly 30,000 miles with an unknown fuel additive. GM has stated that backpressure levels are rising on this vehicle due to additive deposits.

There are several unresolved issues with respect to the applicability of fuel additives to induce self-regeneration. One is the question of how to introduce the additive to the fuel: should it be premixed into diesel fuel at the refinery, or added on-board the vehicle? Blending the additive at the refinery would obviate the need to design an on-board system, but would result in either the addition of the organometallic compound to all diesel fuel, which would result in unnecessary metallic emissions from non-trapped diesel vehicles, or else a special grade of diesel fuel for trapped diesels, which would result in a more expensive and complex distribution system. The on-board approach, utilizing a reservoir of additive and a metering system, may be more practical. The amount of additive required is fairly small and a lifetime supply should be storable with no serious size or weight problems. On-board systems would allow optimization of engine, trap, and additive, and would require no coordination between the auto and fuel industries. Of course, the need to store the additive in a highly concentrated form may preclude those additives from consideration which are toxic in high concentrations (e.g., tetra-ethyl lead).

A second issue concerns the compatibility of the fuel additive and its combustion products (oxides or sulfates) with the fuel injection system and engine hardware. Fuel filter plugging and fuel nozzle and engine deposits have been reported. Manufacturers are currently investigating these problems.

The two most serious, and interrelated, concerns of fuel additives are the environmental consequences of their usage and the possibility of trap plugging with metal deposits. Extensive analysis by Ford has shown that nearly 100 percent of the metallic sulfates and oxides are collected in the trap, and thus, only negligible amounts are emitted in the exhaust. This is very beneficial from an environmental perspective, since some of the metals which have been used so far, such as lead and copper, are quite toxic. Many manganese compounds are considered hazardous as well. There still remain concerns about the storage and ultimate disposal of on-board systems utilizing hazardous substances. As already mentioned, the environmental ramifications of different fuel additives must be a basic criterion for additive selection.

The fact that the metallic compounds are collected and stored in the trap-oxidizer raises the possibility of the trap plugging with metallic deposits. Both Ford and VW reported such problems in their initial vehicle tests. Optimization of trap size and design is one possible solution to trap plugging, but it has not yet been proved that a trap can function satisfactorily with fuel additives for 50,000 miles.

In summary, the utilization of fuel additives to allow self-regeneration is a recent development which was not considered a plausible option at the time of the Feasibility Study. Now it is considered to be one of the leading alternatives for many manufacturers. Results to date have been very promising. Additive systems have been studied less than positive regeneration systems, but they are conceptually simpler, and would likely require less vehicle/engine modifications for production. Should the problems discussed above be resolved, fuel additives would be the regeneration system of choice for most vehicle manufacturers.

C. Regeneration Control Systems

1. Positive Regeneration

Positive regeneration requires the application of an on-board system to initiate and control the regeneration process. This was the most undefined area of trap-oxidizer development at the time of the Feasibility Study. The Technology Study examined regeneration control systems in greater detail and that analysis will be summarized below.

There are three basic functions of any regeneration control system: to determine when regeneration is required, to initiate the regeneration process, and to confirm that regeneration is complete. Other functions, such as determining whether regeneration is possible or allowable under current engine operating conditions, and monitoring the regeneration process for dangerous conditions such as excessive peak temperatures, will also be necessary on many regeneration control systems. For example, exhaust stroke fuel injection produces regeneration with catalyzed wire mesh traps only when exhaust gas temperatures are above a minimum level. Thus, a regeneration system utilizing exhaust stroke fuel injection would have to include control logic to ensure that the minimum temperature was exceeded before initiating regeneration.

Regeneration control systems can be divided into two general parts: 1) the identification and design of a suitable control logic which will ensure effective regeneration, and 2) the application of system components which will implement that control process. The components of a regeneration control system will consist of sensors, actuators, and a mechanism for control logic.

The first step, the identification of the conditions permitting regeneration and design of a suitable control logic, is a fairly straightforward yet time-consuming function. In order to define the operational requirements of the control system, it is necessary to understand the characteristics and limits of the trap regeneration process. Doing so requires extensive testing of specific engine/trap/regeneration systems, which manufacturers have only been able to do relatively recently. Manufacturers now have considerable data concerning the minimum particulate, oxygen and temperature levels, and time necessary for effective regeneration, as well as the maximum particulate loadings and inlet temperatures which can be permitted without risk of overheating the trap. Manufacturers have had time to determine these characteristics for different engines and regeneration systems. Once these limits are known, prototype control logic can be designed to maintain conditions within acceptable limits.

Much progress has also been made in the area of control systems. Several sophisticated control systems have been designed, fabricated, and installed on experimental vehicles, though details have often not been publicly available. For example, Ford has developed a fuel burner regeneration control system which carries out the entire process with the push of a button, and includes the ability to abort if certain conditions necessitate it. Johnson Matthey has also developed the necessary logic to control its HC and CO enrichment system under in-use conditions.

To date, the regeneration systems have still required human initiation. Production systems will have to be completely automated, of course. The final step in perfecting the control process will involve extensive testing to confirm that the control system successfully maintains regeneration conditions within acceptable limits under all possible circumstances. As a result of such testing, refinements to the prototype design are likely.

The regeneration control system must also include hardware which can successfully and reliably implement the control logic. Likely components include sensors, actuators, and a central processing unit. These items are either generally available today or should be available very soon.

Depending on the regeneration mechanism used, a wide variety of sensors may be required for parameters such as exhaust and trap temperature, engine revolutions and load, burner ignition detection, etc. With the exception of the trap temperature and burner ignition sensors, all of these now exist and are in use on production vehicles. High-temperature thermocouples would probably suffice for the trap temperature and burner ignition sensors. Every regeneration control system would also require some indicator of particulate loading in the trap. Given the importance of backpressure on vehicle fuel economy and performance, and its direct relationship with particulate loading for a given trap, a backpressure sensor would be the ideal solution. At the time of the Feasibility Study, the Agency was doubtful that backpressure sensors of sufficient durability and reliability could be developed. Other alternatives, such as using mileage or engine revolution counters as alternatives to direct measurement of backpressure, were discussed in the Feasibility Study instead. However, the situation now appears to be quite different. Ford stated at the public hearing on this rulemaking that it was already testing a backpressure sensor developed for this purpose and VW stated that it did not consider such sensors to be a major problem. The Technology Study concludes that it is "extremely probable" that a suitable backpressure sensor will be available for production regeneration systems in 1987.

Actuators which would be required for regeneration control systems include valves, solenoids, relays, and possibly remotely operated accessory clutches for air pumps. Except for some actuators which might be used on fuel burner systems, these are all available and have been used on production vehicles. Ford has investigated the types of actuators which would be necessary on burner systems and has not reported any serious concerns in this area.

As discussed earlier, it is expected that by the mid- to late-1980's many diesel manufacturers will turn to electronically controlled fuel injection systems. Such systems will use microprocessors to determine the optimum fuel delivery rate and injection timing based on information provided by a variety of sensors. Control logic for trap-oxidizer regeneration control systems would be simply one additional function for vehicles already equipped with microprocessors. Those vehicles which maintain mechanical fuel injection would have to have a separate logic system. Still, this should not be a difficult technical task. Most of the control functions for trap-oxidizer regeneration are on/off functions, rather than continuous variables. Adding control logic of this nature will be relatively straightforward compared to the sophisticated electronics systems which have been developed to handle multiple continuous variables in three-way catalyst, closed-loop emission control systems on many current gasoline-fueled vehicles.

In conclusion, none of the tasks associated with positive regeneration control systems will be technically infeasible. Some aspects of the problem, such as defining the operational limits of the engine/trap/regeneration process, have been time consuming. Other tasks, such as the development of a suitable backpressure sensor, will take more time, but indications are that these problems will soon be successfully resolved. Significant progress has occurred in regeneration control system design in the past year. The primary work remaining will be additional testing of prototype systems resulting in refinements and improvements.

2. Self Regeneration

Self-regeneration trap systems would, by definition, not need any control system. Self-regeneration systems might incorporate a fail-safe system to prevent excessive particulate loading and resultant trap overheating, such as a simple bypass valve venting exhaust around the trap. Positive regeneration systems might need such a mechanism as well. The fact that self-regeneration traps would not require control systems is a major advantage in terms of simplicity and cost.

D. Overall Evaluation of Status of Trap-Oxidizer Development

On the basis of the information analyzed in the Feasibility Study and the information which the Agency has obtained in the past year, the Agency has concluded that the automotive industry is at a very advanced stage of trap-oxidizer development. Collection efficiency, backpressure, and durability characteristics are acceptable when regeneration conditions are adequately controlled. Considerable progress has been achieved in positive regeneration system design and several prototypes have been tested. Only fairly routine engineering tasks remain to integrate and automate regeneration control systems which could be installed in fleet vehicles for additional testing. The development of self-regeneration systems is a very significant advancement in trap-oxidizer development. Although the development of these systems is not quite as advanced as positive regeneration systems, the technical problems are generally conceptually simpler and will likely require less time for design and assurance testing. In addition, the high level of manufacturer interest in fuel additives indicates the promise of self-regeneration.

The Technology Study confirms the Agency's position that trap technology is at a very advanced stage. The Technology Study, based on information from automotive emission control researchers in addition to written submissions to EPA, identified three trap-oxidizer systems (trap design and regeneration mechanism, plus control system if necessary) which it considered to be at an advanced stage of development: 1) ceramic monolith trap/regeneration with fuel burner, 2) catalyzed wire mesh trap/regeneration by HC and CO enrichment (such as exhaust stroke fuel injection), and 3) ceramic monolith trap/self-regeneration using fuel additives. The Technology Study concluded that there are no technical uncertainties regarding the feasibility of the ceramic monolith/fuel burner system. It considered successful development of the catalyzed wire mesh/HC and CO enrichment system to be "highly probable" and development of the ceramic monolith/fuel additive system to be "probable" in the near term, and that both of these systems would be preferred if feasible, due to their greater simplicity and lower costs. If these systems did not prove to be feasible, then the fuel burner would be adopted industry-wide.

E. Prototype Development Leadtime

This section will address the issue of how much leadtime is required for vehicle manufacturers to optimize trap-oxidizer systems to the stage where workable prototype trap/regeneration systems can be installed in vehicles for assurance testing. The Feasibility Study had projected that manufacturers would reach this point by January 1983. Based on the comments submitted to EPA in January and February 1983 as a part of this rulemaking, it appears that manufacturers had not reached the assurance testing stage by January. Nevertheless, most manufacturers are very close to having workable prototype designs.

As summarized in the previous section, trap-oxidizers are at a very advanced stage of development. The only area where further development is necessary is in regeneration, whether positive regeneration or self-regeneration. No major technical uncertainties exist for positive regeneration systems, such as fuel burners. Remaining design tasks are relatively straightforward engineering problems such as development of high-temperature and backpressure sensors, the automation of the regeneration control system through the use of fairly simple electronics, and preliminary testing of the control systems in order to refine the system designs before the more extensive fleet assurance testing begins. Most of the components for regeneration control systems are already used on production vehicles today, and the experience of automotive designers with sophisticated electronic controls on gasoline-fueled vehicles should be of particular assistance in adapting control systems for diesel vehicles.

Greater uncertainties exist with respect to self-regeneration systems based on fuel additives. There are technical uncertainties with respect to on-board additive storage and metering, although this appears to be a fairly straightforward design problem. Concerns about the impacts of metallic deposits on fuel system and engine parts and the trap itself are more serious, and can be resolved only by additional development and optimization. Given the high rate of progress in the last year with respect to fuel additive development, however, and the understanding which already exists as to the problems and possible solutions, the Agency expects manufacturers to resolve these concerns very soon. Quite possibly the most important questions about self-regeneration systems revolve around the environmental consequences of their usage, with respect to any metallic emissions which could be toxic, and the safety and ultimate disposal of on-board storage systems. EPA stands ready to work with the manufacturers in analyzing such problems.

Of course, it is not necessary that both positive and self-regeneration systems be developed; only one such system is necessary. There are clearly more technical uncertainties remaining with respect to fuel additives than with respect to fuel burners. Many of the uncertainties regarding fuel additives exist because the concept has only recently been under serious investigation. The Agency believes that such questions will be resolved relatively quickly, given the straightforward nature of the problems and the emphasis many manufacturers are putting on the development of additives. Nevertheless, should the additive concept prove unworkable, positive regeneration systems will undoubtedly be available.

Once complete regeneration systems are developed, involving positive or self-regeneration, the vehicle manufacturers can proceed with assurance testing in the field in order to evaluate comprehensively the entire trap/regeneration system design in-use. It is not necessary that a manufacturer have production-ready trap systems available for the assurance testing fleets, since assurance testing is itself a part of the final evaluation process. Rather, the manufacturer must select the most promising trap design/regeneration system combination(s) so that the assurance testing process may begin. The manufacturer may need to include more than one concept in its assurance testing if it is unable to identify one most promising concept, or if it wants to be "safe" in case of failure of any particular design. EPA's analysis of the time necessary for assurance testing leaves the manufacturer enough latitude to perform the testing in two separate phases, so improvements may be made in the midst of the program.

It must be noted that there is evidence that many manufacturers have already undertaken preliminary fleet assurance testing, though typically not with completely automated regeneration control systems. Earlier, the Daimler-Benz testing program in Denver involving high-mileage accumulation with 12 vehicles was discussed. Daimler-Benz has announced that "DBAG will shortly begin a new durability program on a new generation of trap-oxidizers. This program incorporates all results and improvements gained up to this time."[11] Volkswagen has reached the point where it can rank its candidate systems, and has stated that "Volkswagen is cautiously optimistic of meeting a 0.2 g/mi particulate standard in model year 1987."[12] From this statement, EPA infers that VW is not far from commencing assurance testing.

The relatively straightforward nature of the engineering problems which remain, and the progress which manufacturers have achieved in the past year with respect to both positive regeneration control systems and self-regeneration, indicates that manufacturers are very near to workable trap/regeneration systems for assurance testing. The EPA technical staff projects, based on the information available to the Agency as of February 1983, that another 6-9 months of optimization will permit all manufacturers to have workable prototype trap/regeneration systems. This will permit industry-wide assurance testing to begin in the fall of 1983.

F. Production Development Leadtime

After the successful demonstration of prototype trap/regeneration systems, additional development will be required to prepare trap-oxidizers for mass production. In considering this aspect of the development continuum for the two positive regeneration systems (i.e., the ceramic monolith/fuel burner and wire mesh/HC and CO enrichment systems), the Feasibility Study found that a total of 25-33 months would likely be necessary. The critical path elements within this schedule of events consisted of a 7-9 month period for assurance testing and an 18-24 month period for acquiring production facilities and tooling. These production development projections are considered to be far more straightforward than the estimates for prototype development because no technological advances are necessary. Therefore, the Agency finds that these projections continue to be reasonably accurate and that they need not be revised.*

The information EPA acquired during the rulemaking revealed a new control technology that was not explicitly considered in the above leadtime schedules. This technology, the ceramic monolith/fuel additive system, was not clearly identified at the time the Feasiblity Study was completed. The available data on this self-regenerating system is limited and does not allow an independent quantitative assessment of the requisite production development leadtime. However, the leadtime requirements can be qualitatively assessed by comparing this system to the positive regeneration systems.

As discussed previously, the ceramic monolith/fuel additive system is inherently simpler than the other systems because of its self-regenerating characteristics. This aspect of the system should result in reducing the necessary

* It should be noted, however, that these conservative leadtime projections consider only the time necessary to enable manufacturers to introduce trap-oxidizers on most or all models requiring them in order to meet the 0.2 g/mi particulate standard on a nationwide basis.

production tooling leadtime in comparison to that required for the positive regeneration systems, because there are likely to be significantly fewer and less complex parts. Therefore, at the very least, this suggests that the leadtime for the ceramic monolith/fuel additive system would be best represented by the lower end of the 25-33 month projection. Until additional information becomes available with which to make this judgment more conclusively, however, EPA will assume conservatively that the same amount of production leadtime is required by both positive and self-regeneration systems (i.e., 25-33 months).

IV. Conclusion

A. Applicable Model Year

Now that the total leadtime requirements have been assessed, this information can be used to project the model year in which trap-oxidizer equipped vehicles can be mass produced. Assuming that successful prototype trap/regeneration systems are demonstrated in the fall of 1983, and that an additional 25-33 months are necessary to develop the systems fully, EPA projects that trap-oxidizers should be available for production sometime between the fall of 1985 and the summer of 1986. Because vehicle production for each model year generally begins at the end of the summer of the previous calendar year (i.e., August) the above completion dates show that trap-oxidizers will be feasible on a nationwide basis for the 1987 model year. Therefore, based on an assessment of the information submitted during the rulemaking, EPA concludes that delaying the 1985 particulate standards for two years is sufficient to allow for the complete development of trap-oxidizer technology.

The 2-year delay is supported by the Technology Study which, as previously described, was an independent assessment of trap-oxidizer feasibility. This study concluded that the successful development of trap-oxidizer technology for introduction in the 1987 model year was highly probable for both the ceramic monolith/fuel burner and wire mesh/HC and CO enrichment systems, and was probable for the ceramic monolith/fuel additive system.

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